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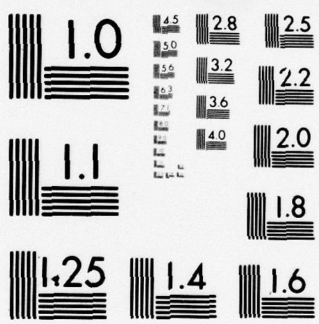

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EVALUATION OF AN IMPROVED PARACHUTE TEST DATA ACQUISITION SYSTEM

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Preface

This project determines the feasibility of employing digital technology to collect and store data obtained during an airborne drop of a parachute and dummy test package. The digital data acquisition system is housed entirely within the dummy. This report analyzes the design requirements for the modules which make up the parachute test Data Acquistion System (DAS) and describes approaches for measuring and storing parameters at the high data rates typical during parachute tests. A laboratory prototype constructed during this project is evaluated. The prototype storage media is the Rockwell 256 kilobit magnetic bubble memory (RMB-256).

Many thanks to Mr. Mike Higgins, Aeronautical Systems Division, Life Support System Program Office (ASD/AELT) for his guidance and expertise in explaining the details of parachute testing, as well as to the 6511th Test Squadron at Edwards AFB for supplying representative sensors for prototype evaluation. Also, to Mr. Bob Durham of AFIT and the School of Aerospace Medicine at Brooks AFB for their invaluable assistance in obtaining hardware for the evaluation system. For the crucial assistance from my advisors: Dr. Ross, Dr. Kabrisky, and Dr. Hartrum, I am sincerely thankful. Finally, for her patience and encouragement, my deepest gratitude goes to my wife, Judy.

Gary A. Richardson

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List of Abbreviations

A/D	Analog to digital
AM	Amplitude modulation
CCD	Charge coupled device
CG	Center of gravity
CMOS	Complementary metal oxide semiconductor
D/A	Digital to analog
DAS	Data Acquisition System
DC	Direct current
DI	Deployment Initiation
EAROM	Electrically alterable read only memory
FDM	Frequency division multiplex
FM	Frequency modulation
HMOS	High noise immunity logic metal oxide semiconductor
HOL	High order language
HZ	Hertz (equals one cycle/second)
IC	Integrated circuit
K	1024 (in digital memory descriptions)
LSI	Large scale integration
MBM	Magnetic bubble memory
MOS	Metal oxide semiconductor
MTBF	Mean time between failures
NASA	National Aeronautics and Space Administration
PAM	Pulse amplitude modulation

PCM	Pulse-code modulation
PROM	Programmable read only memory
RAM	Random access memory
ROM	Read only memory
SNR	Signal to noise ratio
SSD	Steady state descent
TDM	Time division multiplex
TM	Telemetry
TTL	Transistor-transistor logic

Abstract

This project confirms the feasibility of a sixteen channel, self-contained data acquisition system that would be suitable to store data obtained during a parachute performance evaluation drop. The overall system is discussed in modular fashion to allow generalization to other portable data acquisition systems that must accept data at high rates but over relatively short time intervals. The storage medium for the proposed system utilizes magnetic bubble memory devices.

EVALUATION OF AN IMPROVED PARACHUTE TEST DATA ACQUISITION SYSTEM

I. Introduction

Background

When a critical system of a high performance aircraft fails, the emergency parachute is often called upon to save the crew. When needed, the parachute is required to function safely and reliably over a wide range of ejection speeds and altitudes. Thus, the operational testing of emergency parachutes requires highly reliable, rugged data collection equipment.

Because of the importance of the data collection system in the testing of parachutes, Aeronautical Systems Division, Advanced Systems Division (ASD/AELT) at Wright-Patterson Air Force Base, Ohio, is constantly seeking to improve upon the data acquisition systems used in measuring and recording rapidly changing parameters that are typically observed during a parachute evaluation. In particular, there is keen interest in the possibility of employing microprocessor control in data acquisition systems to significantly improve upon overall capability and flexibility. Interest is also expressed in storing the collected data on board the data acquisition system for

recovery after the test rather than telemetering the data to ground-based stations as with the present system. This feasibility study is undertaken with the cooperation of ASD/AELT and the 6511th Test Squadron, Air Force Flight Test Center, Edwards Air Force Base, California, where present parachute testing is accomplished.

Present System

The existing parachute data acquisition system is built around a Pulse Amplitude Modulated/Frequency Modulated (PAM/FM) radio telemetry (TM) system and three-space position cinetheodolites. A cinetheodolite station is a ground-based, optical tracking telescope which records azimuth and elevation information relative to the station platform. Triangulation of data collected from several stations allows the position of the test vehicle to be calculated. Time synchronization between TM and cinetheodolite data is provided by National Bureau of Standards radio station WWV, Fort Collins, Colorado. The PAM/FM TM transmitter is housed along with supporting hardware in the neck cavity of torso dummies or the chest cavity of articulated dummies. Information from sensors is transmitted by the TM unit (as an analog signal) to a ground-based receiving station located near the drop zone. The information on the various channels is recorded on magnetic tape for later playback for printout on oscillograms. Typical

sensors used in data collection are: two tensile force (strain link) transducers, three linear acceleration transducers, and a triaxial rate transducer. One strain link transducer is mounted on each parachute riser and can measure forces into the 7500 pound force range. The linear acceleration transducers are rigidly positioned along three orthogonal axes that pass through the approximate center-of-gravity (CG) of the dummy. These transducers are selected for G force measurement in the range from -25 to +25 Gs. Higher G force reading transducers are sometimes required depending on the nature of the test. When used, the triaxial rate transducer is mounted near the dummy CG, and rotation rates of up to -1500 to +1500 degrees/second are measured. In addition to the above sensor channels, two additional TM channels are used. One is to transmit the level of the 28-volt battery and the other is a zero to 5-volt reference channel for ground station synchronization. Because of undesirable structural resonances within the dummy, noise reduction techniques are employed during oscillogram printouts. Also, the galvanometer pen used in producing oscillograms has flat response to only 60 hertz (Hz).

Information obtained from the three-station cinetheodolite tracking is used to compute test package speed, acceleration, dynamic pressure, and oscillation angle. Rawinsonde data on wind velocity, atmospheric pressure, and air temperature at 1000 foot increments, as well as surface measurements of this data, is used to correct for

effects that these parameters have on cinetheodolite data. This information is digitized for data processing on a large-scale digital computer.

Along with cinetheodolite film, aerial and ground-to-air photography is performed using 16mm photographic equipment with frame rates from 24 to 400 frames/second.

Proposed System

Continual advances in digital hardware have made it possible to consider a data acquisition system with digital rather than analog channels. Even with a telemetry-based system, there are reasons for this approach. When the outputs from the sensors are converted to digital values, they can be transmitted to earth with Pulse Code Modulation (PCM). This form of transmission is highly immune to noise. Also, since the received signals are really digital in nature, they can be processed immediately or stored in digital format for later processing. While analog signals can be converted to digital equivalents at any point in the data acquisition process, early conversion to digital format will reduce the noise component in the recorded signal.

If the test package can be protected from destruction during the evaluation process, then the data acquisition system could be designed to store the collected data on board the test vehicle. This would eliminate the possibility of the telemetry system inducing errors into the sampled data during the transmission process. To store all

collected data within the data collection system, a memory with high density and low power consumption is needed. While not essential, it is desired that the memory also be nonvolatile so that power can be removed from the memory without losing the stored data. Otherwise, a higher capacity power supply would be needed to hold the stored data until it could be extracted.

There are many techniques available to transfer the incoming data into memory. One alternative is to design a circuit that simply transfers the digitized data to its own memory and use one of these modules for each data channel. The obvious redundancy of this concept suggests that this is an overly expensive approach with higher power consumption, size, and weight than necessary. However, this method may have to be used if channel data flow rates are very high. A better approach is to construct a single circuit for transferring data to memory but have the channel selection determined by a system controller.

One possible type of hardware for use in the controller is the microprocessor. By selecting this as a data acquisition controller, the potential of the data acquisition system far exceeds that of a simple passive data recorder. The system functions can be easily altered by changes in the software, and, since the microprocessor has access to the data values, the overall system can make real-time decisions based on the values of the incoming data.

This paper discusses a proposed parachute test Data Acquisition System (DAS) that will function under micro-processor control. The proposed DAS will be capable of sorting data from up to sixteen channels with channel sample rates under software control. For additional utility, two eight-bit parallel ports will be provided to interface to the users' test package. The ports can be conditioned as either digital inputs or outputs. As inputs, individual bits of a port could be used by the test package to signal the DAS about important events created by the test package. For example, a mechanism within the test package may deploy the parachute. This condition could be an input to the DAS to mark the event of deployment initiation. Similarly, a port (or part of a port) could be programmed as an output to interface with the test package. An example of this would be using selected events (such as deployment initiation) to ignite flashbulbs mounted on the dummy. This technique would serve as a useful method to synchronize the occurrence of a significant event recorded in the DAS along with the photographic record of the test.

While a photographic record of the test drop is important, the three-station cinetheodolite is mostly used for determining parameters that might be more accurately measured by sensors mounted on the dummy. In addition to the two riser force channels, three linear acceleration and three angular rate channels which are used on the

present system, the addition of channels for dynamic pressure, low-speed velocity, and pressure altitude might allow the user to test parachutes on a test range not equipped with TM or cinetheodolite equipment.

Statement of the Problem

This project investigates the feasibility of a self-contained, microprocessor controlled data acquisition system suitable for collecting and storing data typically gathered during an actual test of a parachute. Along with size, weight, and power restrictions typical of such self-contained hardware, there are the additional problems related to the environment under which the parachute is tested and the rapidity with which measured parameters can change. Also the proposed DAS must be highly reliable and cost effective.

Assumptions

This project is primarily concerned with feasibility of the proposed DAS. Thus, it is assumed that a sensor's electrical output is an accurate representation of the physical parameter being measured. Also, it is assumed that data reduction methods exist (or can be created) to allow meaningful conclusions to be drawn from a given parachute test.

While not absolutely essential, it is most desirable that the user have basic knowledge of digital circuits and computer programming. This will allow the user to optimize

the operation of the DAS for a specific parachute test by changing only the microprocessor software which controls system performance.

Scope

A system design for a proposed DAS has been created and implemented in modular form on a laboratory prototype which can serve as a development system for the DAS. With this development system, the problems involved in gathering data from up to sixteen sensors at data flow rates required in actual parachute tests have been evaluated. Similar analysis has been conducted on the problems involved in storing the collected data in a memory device. Finally, the potential for digital filtering of the incoming data has been investigated in order to reduce the amount of data that has to be stored by rejecting data that is not significant to the experiment. The concept of digital filtering involves selection criteria much broader than just frequency alone. By eliminating unneeded data points from storage, there is the possibility for reducing memory size along with corresponding reductions in system size, weight, power consumption, and cost.

Related Work

One important aspect of the design for a digitally based DAS is the type of memory that is to be employed. Today's technology offers a wide selection of memory hardware. While this topic will be covered in more detail

later, one relatively new device is the Magnetic Bubble Memory (MBM). The use of magnetic bubble memory devices in data acquisition systems has a promising future (Hoffman, 1976; 1976b). Of particular interest is the use of bubble memory recorders for space applications (Bohning, 1979) which strongly suggests the potential that bubble memory devices have for reasonably low power consumption, high storage density, and (perhaps most important of all) high reliability in a harsh environment. Two AFIT theses (Hill, 1978; Jolda and Wanzek, 1977) have investigated the use of bubble memories in a self-contained data acquisition system designed to record physiological data from an aircrew. In many respects, this physiological data recorder is very similar to the proposed parachute test DAS. However, parachute test DAS recording time is measured in minutes while the physiological data recorder time is measured in hours. Also, data rates encountered in parachute testing are much higher than most physiological parameters. Finally, packaging is more critical for a parachute test since G forces observed in parachute tests are much higher than those observed in an aircraft.

Plan of Attack

This work is a study of the feasibility for a new generation of data acquisition system that is suitable for use in the harsh environment encountered in testing parachutes. First, the nature of the data acquisition problem

is discussed to include the impact that sampling theory has on the entire data collection process. Similarities between existing parachute test DAS's and the proposed DAS are covered as well as the tradeoffs in performance that exist between existing and proposed systems.

Once the conceptual validity of this proposed system is determined, a more specific look into actual hardware implementation of such a system is conducted. This includes discussion of devices suitable for use in this system which are now (or soon will be) offered on the commercial market. Specifically, this discussion includes digital memory devices and analog to digital conversion hardware. Other topics related to the suitability of microprocessor control of the system are also covered. The result of this discussion leads to a complete description of the proposed system in terms of functional modules.

Based on the system description, a laboratory prototype has been constructed which serves as a development and evaluation tool for the proposed DAS. The system is configured in a top-down structure to allow for ease in modification as well as to allow this development system to be generalized to other similar DAS's. Laboratory evaluation of this prototype is reviewed, along with a discussion of findings that impact an airborne prototype DAS.

II. System Concept

Approach to Acquire an Improved DAS

To fully evaluate the potential for a proposed DAS, it is most useful to analyze the new system along with its existing counterparts. Such an analysis serves not only to point out strengths and weaknesses in both systems, but, also, it may provide users of the current system with suggestions with which to implement interim modifications to enhance an existing DAS's performance. Such interim changes to an existing system may not prove cost effective in the long run, but enhanced system performance (with minimum expense) may be worthwhile. With only slight changes being made to an existing system, an improved DAS can be evaluated simultaneously with regular parachute testing. While it would be unrealistic to assume that modifications would not result in some system failures, properly engineered design changes to an existing system may provide significant performance gains to justify the risk. Thus, complete re-validation and re-verification of the improved system would not necessarily be required because the majority of the system has already been proven.

While a gradual system improvement approach may serve to obtain a slightly improved DAS in minimal time,

careful consideration should be given to the impact of greatly enhanced DAS's in future tests. Such DAS's may be entirely redesigned with little or no similarity to the existing system. This may necessitate the use of all new hardware and an abrupt changeover to the new system. In other words, the entire system environment would be configured to achieve maximum performance, accuracy, flexibility, and reliabiity from the new system. For example, an improved DAS may require entirely different equipment for its use: a new test dummy, sensor package, power module support in hardware, and test equipment. System validation and verification would require complete testing of all system funcions in the environment in which it is employed.

In comparing the two approaches mentioned above, toward acquiring an improved DAS, the overall impact of the proposed DAS on long-term testing costs is the most important factor. In properly engineered equipment, it is usually found that minor modifications usually lead to only minor improvements in performance and, therefore, only minor reductions in overall testing costs. New systems, if they are well conceived and engineered, have the greatest potential for significantly reducing the costs of testing, but such systems rarely display cost reductions initially because of hardware procurement and development costs. Thus, a natural tendency is for the system user to continue to use the equipment he has until interest is expressed to obtain it by some museum.

While the above statements are obvious to those involved in the procurement of new systems, it is equally true that, in many specific instances, the first organizations to employ new technology in their work have paid a high price for the learning experience. It is very likely that if the ramifications of employing this new technology had been more fully understood, then the transition to new generation hardware would have been considerably more enjoyable. It is hoped that this paper will aid in exploring the potential for digital technology in the area of data acquisition. To accomplish this task, the application of sampling theory in the data acquisition process will be examined.

Frequency Division Multiplex System

To determine what constitutes an improved parachute test DAS, the concepts employed by existing DAS's to store sensor data will be comparatively analyzed and the various advantages and disadvantages of the system will be discussed. This analysis will assume that the sensor output tracks the physical parameters being measured with negligible error and that system modules perform their assigned function.

The transmitter portion of a hypothetical N-channel telemetry-based data acquisition system is shown in Fig. 1. This diagram shows all major functional blocks that make up the hardware that is contained within the test dummy. First,

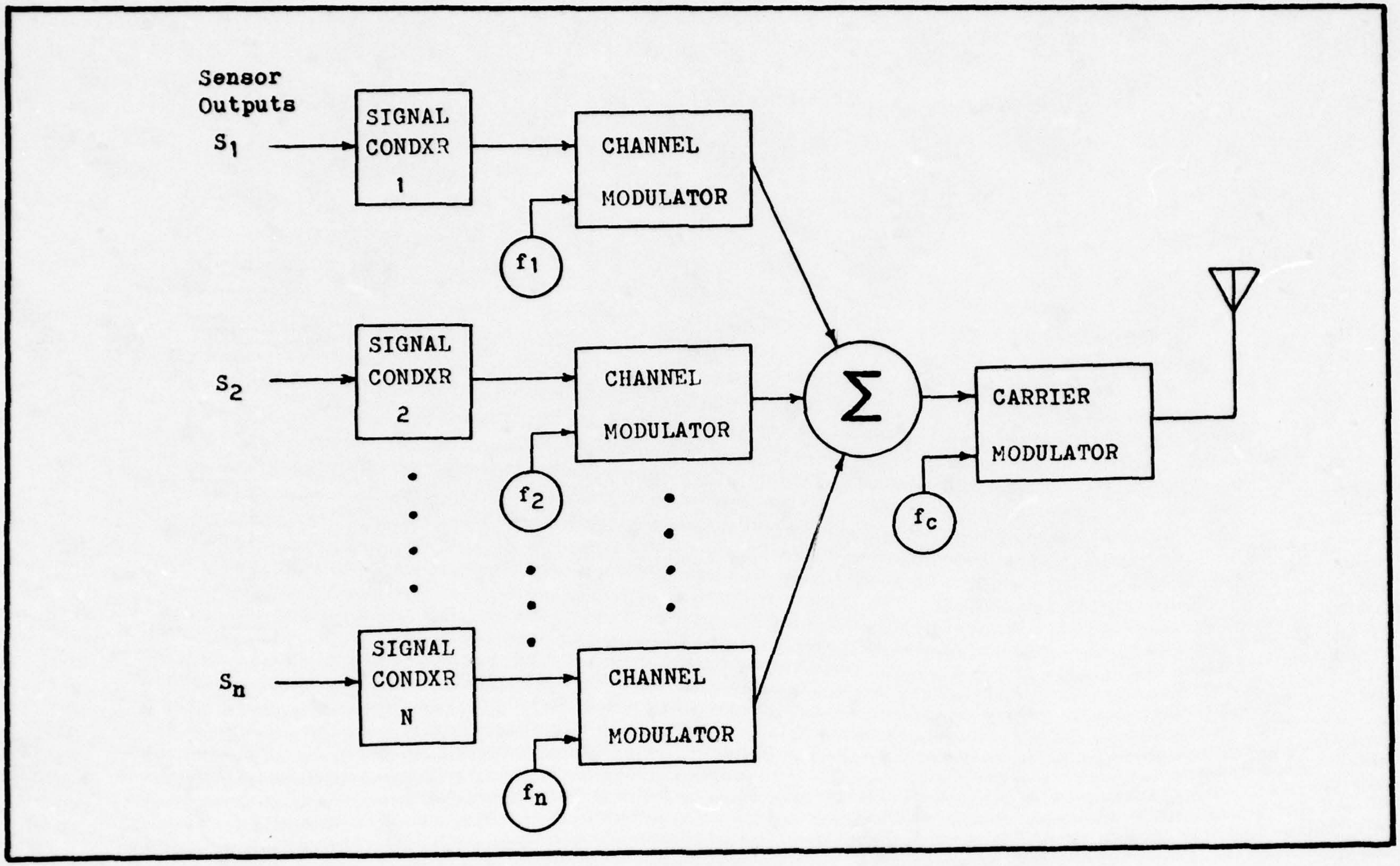

Fig. 1. Telemetry transmitter block diagram

the output from each sensor is passed through a signal conditioner module. This module provides the appropriate gain and power needed to effectively drive each channel modulator. For example, maximum voltage output of a force (strain link) sensor is usually on the order of 10 to 15 millivolts while the linear acceleration sensor output ranges from 0 to 5 volts. Thus, more gain is needed in the signal conditioner module for the strain link sensors than for the linear acceleration sensors. Another important function of the signal conditioner module is to limit the bandwidth of each sensor channel. It is essential that this be done to insure that the overall bandwidth will also be limited (Stark and Tuteur, 1979:297). This is necessary because the bandwidth of each channel converts via the modulation process to the same bandwidth interposed on the carrier signal f_c. Theoretically, if a given sensor output has infinite bandwidth, it would have to be the only channel used to modulate the carrier signal because a second channel's signal spectrum would overlap with the first channel's spectrum.

The channel bandwidth is also restricted for the practical reason of maintaining the resultant bandwidth of the TM transmission within manageable limits for existing hardware. However, bandwidth must not be limited too much or significant frequency characteristics of a sensor output waveform may be lost. Selection of the cutoff frequency for

the low-pass filter in the signal conditioner will, therefore, depend on the nature of the sensor waveform being observed. In other words, if a sensor output has a high frequency component in its spectra that is significant to the data to be collected, then the cutoff frequency of the low-pass filter should be above this component or the data from this sensor will be distorted when it is processed.

Following signal conditioning, each sensor output is used to modulate its own subcarrier with frequencies $f_1, f_2, \ldots, f_n$. To minimize overall system bandwidth, these subcarrier frequencies should be as close together as possible, but if the subcarrier frequencies are too close together, then adjacent channel frequency spectra will overlap. This situation results in undesired interchannel interference. Proper signal conditioning and selection of subcarrier frequencies will minimize this effect. Not apparent from the block diagram is the problem of interference between all channels. This is called cross talk and is a very real problem in actual hardware. For a more complete discussion of FDM, refer to Stark and Tuteur, 1979:297-301.

Following the channel modulation process, all subcarriers are electronically summed and used to modulate a carrier of frequency f_c. This resulting signal is then transmitted to earth where an inverse process is performed to extract the sensor signals.

The reconstruction of the sensor outputs is accomplished by hardware illustrated in Fig. 2. After

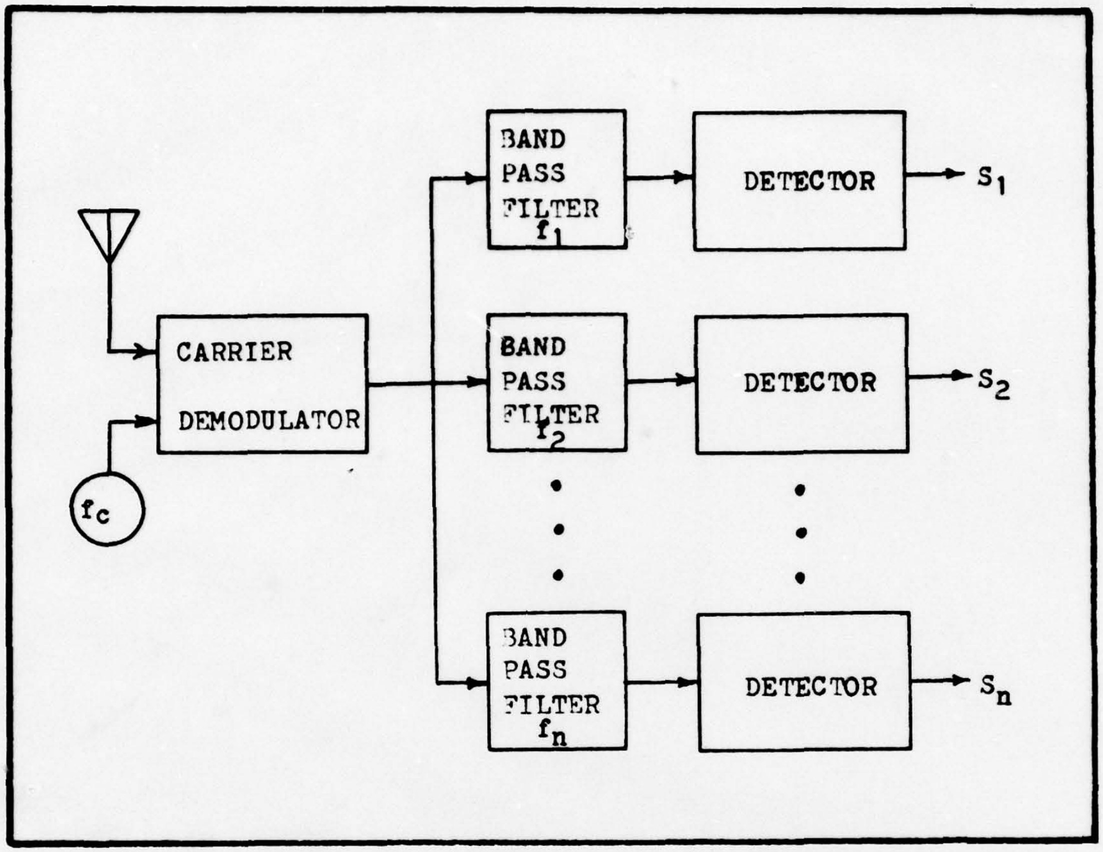

Fig. 2. Telemetry Receiver Block Diagram

initial demodulation of the transmitted signal, the resulting waveform is simultaneously passed to a series of band-pass filters: one for each sensor channel. The center of the pass-band is the corresponding subcarrier frequency used in the telemetry transmitter. Obviously, the bandwidth of each band-pass filter must be such that interference does not occur from other channel spectra, but the bandwidth should be large enough to recover all of the information in the original subcarrier. After filtering each reconstructed subcarrier is detected and the resulting signals recorded for later analysis.

This telemetry-based DAS is commonly called a Frequency Division Multiplex (FDM) system. That is, each channel is converted to its own image in a frequency domain to simultaneously transmit all channels to a receiving station. In practice, several receiving stations may be employed to further insure that the transmitted signal is picked up with the test package in all possible locations and orientations on the test range. Note that the transmitted signal can occupy a fairly wide bandwidth depending on the number of channels desired. One solution to some of the problems encountered in a multiplexed transmission system is to avoid multiplexing altogether by using a separate transmitter for each channel. This would significantly increase the telemetry transmitting unit power consumption, and, therefore, this method is not desirable for portable TM transmitting packages. It is important to realize that even with a single channel TM DAS that it is impossible, even in theory, to exactly reconstruct the sensor output at the TM receiver because to do so would require infinite bandwidth. Fortunately, realizable bandwidth restrictions can be made for physical parameters which are naturally band limited. Therefore, the technique of channel multiplexing is quite useful in efficient data acquisition systems (Stark and Tuteur, 1979:137).

Some of the DAS's currently being used at Edwards AFB to record parachute test data are based on the frequency division multiplex concept. Typically, Frequency Modulation

(FM) is chosen for both the channel and carrier modulation. FM is capable of achieving higher signal to noise ratio (SNR) for the same transmitter power than an equivalent system employing Amplitude Modulation (AM). Drawbacks to FM versus AM modulation are that FM requires larger bandwidth than AM signals of equal quality and FM systems are generally more complicated than AM systems. With the use of both AM and FM modulation in TM systems, hardware implementation problems usually require the need for system calibration prior to (or during) each use. That is, for a given channel input, the recorded output will not be a constant over time. Fortunately, such drifting is usually a relatively slow phenomenon. Thus, pre-test calibration will often suffice to establish the ability to accurately reconstruct the values of the channel input.

Another drawback to systems employing FDM is that for each additional channel there is a significant increase in the system bandwidth required to transmit the multiplexed signal. Eventually, a large enough bandwidth will be reached which precludes practical implementation using cost-effective hardware. In order to multiplex more channels in realizable systems, it is often desirable to multiplex in the time domain.

Time Division Multiplex System

Figs. 3 and 4 show a multiplexed TM system that functions in the time domain rather than in the frequency

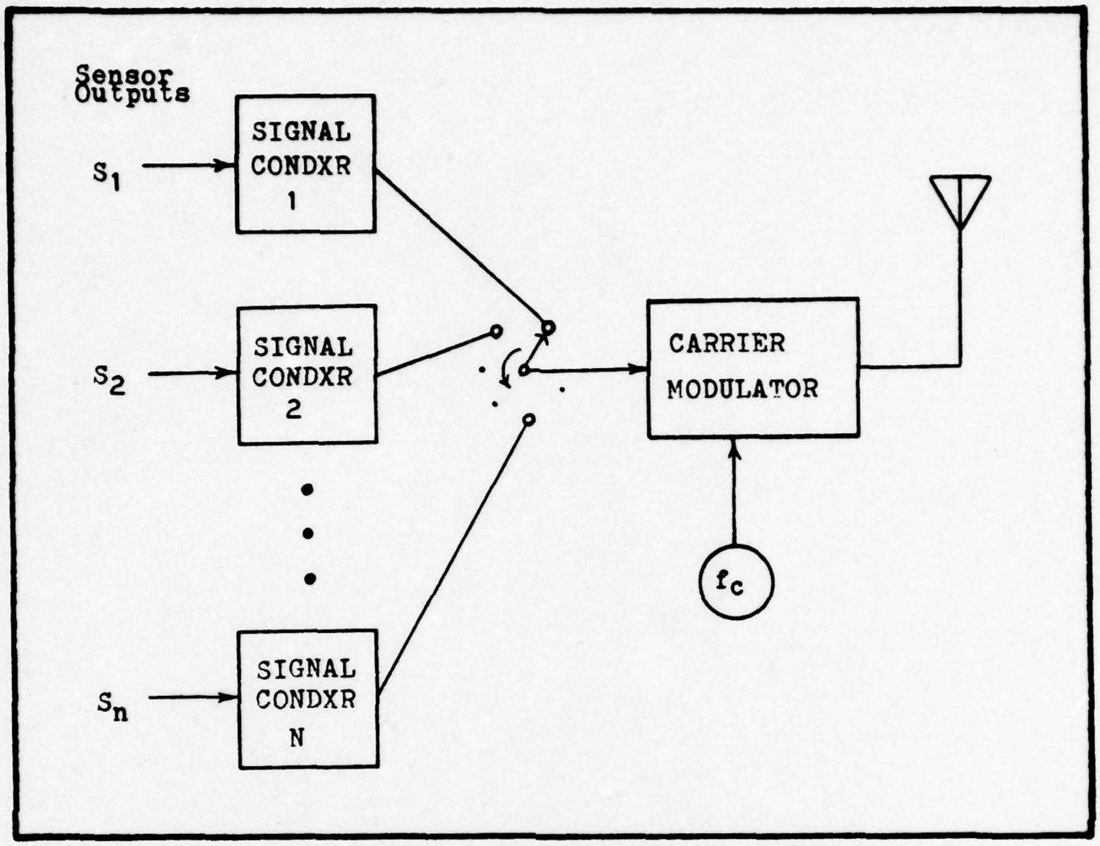

Fig. 3. Time division Multiplexed TM transmitter

domain. In operation, each channel, in turn, is sampled and transmitted to the receiver where the signal is demodulated and routed to the appropriate signal restorer which converts the samples (which appear as a series of pulses) into a reconstructed sensor output. One difficulty in implementing such systems is the problem of synchronization. In other words, some method is required to insure that each channel transmission is routed to its correct signal restorer. Such synchronization can be achieved by a control external to both transmitter and receiver, or synchronization information can be transmitted in addition

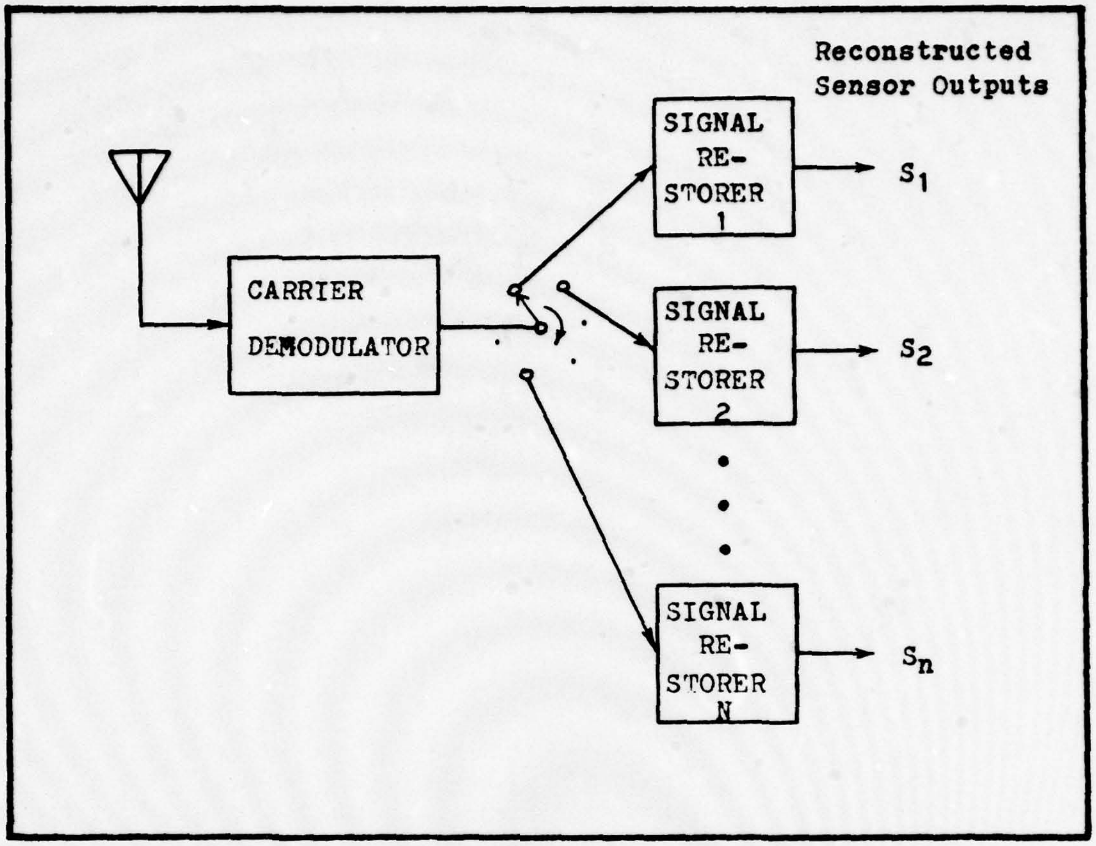

Fig. 4. Time division Multiplexed TM Receiver

to the channel information. Because of the additional complexity of providing external synchronization to both transmitter and receiver, the choice of a transmitted synchronization signal is often made. At Edwards AFB, a 32 channel TDM TM system is employed using channels 28 through 32 for a synchronization signal. Very unlikely values are selected for these channels to prevent the possibility of data values in the other channels appearing as a synchronization signal. Breaking synchronization lock is a very real problem in practical TDM systems.

At first, it would appear as if the cross talk problem encountered in FDM systems would not be present in TDM systems. It can be shown (Stark and Tuteur, 1979:152) that a form of interference does exist between channels that is referred to as intersymbol interference. The nature of the interference can be visualized by considering a waveform being generated within a realizable TDM system. Since this waveform cannot instantaneously change, its value will influence the system response to the value of the next channel selected. In theory, such intersymbol interference encompasses all channels of a TDM system, but practical systems of good engineering design can make the effect of intersymbol interference negligibly small (Stark and Tuteur, 1979:152-156).

The Sampling Process

Another potential problem with TDM systems is that the sensor information is not being transmitted continuously as in the case of FDM systems. The question becomes: can samples from a waveform be used to reconstruct the original waveform and, if so, at what rate should the samples be taken? The uniform sampling theorem (Stark and Tuteur, 1979:138) (also known as the Whittaker-Shannon sampling theorem) states that it is possible to completely reconstruct a band limited waveform from samples taken at least twice the rate of the highest frequency component in the waveform. This minimum sampling rate is also known as

the Nyquist frequency. If frequencies are introduced into the waveform that are greater than one half the Nyquist frequency, then a condition known as spectral folding (or aliasing) will occur (Stark and Tuteur, 1979:141). In complex waveforms, aliasing will distort the reconstructed waveform to a degree proportional to the amplitude of the components whose frequencies are greater than one half the Nyquist frequency. These offending frequencies are reflected in the reconstructed waveform as lower frequencies. As the unwanted frequency approaches the Nyquist frequency, the sample reflects a frequency of lower and lower frequency until, at the Nyquist frequency, the unwanted frequency appears as a DC potential whose amplitude depends on the amplitude of the undesired frequency and the relative phase of the sampling process to the unwanted frequency. In comparing TDM to FDM signal conditioning, it is equally important to band limit the sensor waveforms to insure that the sensor waveforms can be reconstructed. The difference between the two methods is that unlimited bandwidth in a FDM system could cause cross talk while an unlimited bandwidth in a TDM system could produce aliasing which would cause distortion to be introduced into the reconstructed waveform.

It is important to realize how the uniform sampling theorem applies to the data acquisition process. For example, assume that a physical event occurs that produces a sensor output as shown in Fig. 5A. It is obvious that a

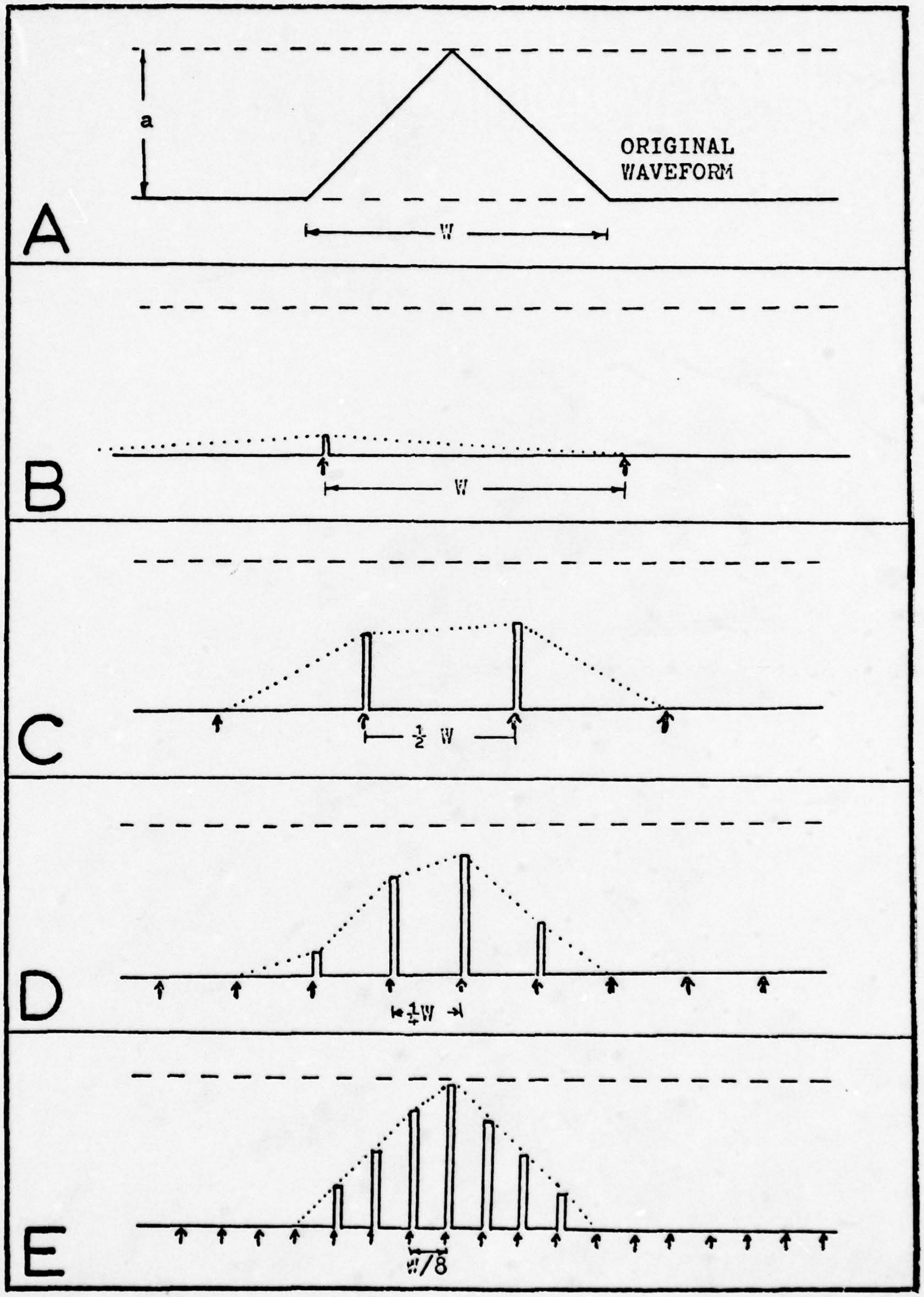

Fig. 5. Effects of sampling rate on a non-periodic signal.

sample interval of W is too low. This is emphasized in Fig. 5B: the sampling phase was such that the occurrence of the physical event was almost entirely missed. In any event, the waveform could not be reconstructed from the samples. What is important to note for those that are not thoroughly familiar with the ramifications of sampling theory and Fourier analysis is that sampling at the "apparent" Nyquist frequency (interval between samples equals W/2) cannot provide an accurate reconstruction of the original waveform. The reason for what appears to be a contradiction to the sampling theorem is that the triangular waveform of Fig. 5A has significant frequency components at and above 2/W Hz. In Figs. 5D and 5E, the effect of increasing sample rate on the reconstructed waveform can be seen. While not totally relevant to this discussion, it should be pointed out that a true triangular wave (as shown in Fig. 5A) cannot be emitted from a sensor because such a waveform requires infinite bandwidth. Also, linear interpolation between sample values is not necessarily the best reconstruction of the wave possible using sample theory, but as the sample rate is increased this fact becomes insignificant.

Optimal Sampling of Sensors

It is noteworthy that the degree of accuracy of the reconstructed waveform can be affected by the choice of when to sample it (see Figs. 5C, 5D and 5E). Indeed,

when the time between samples was W/2 (Fig. 5C), if a sample had been made at the beginning of the rise of the original waveform, then a linear interpolation of the samples would have resulted in an exact reproduction of the original waveform. This demonstrates that accuracy in the reconstruction of non-periodic waveforms can also be enhanced by proper choice of when to sample the channel. In most data acquisition environments, however, lack of knowledge of the waveform forces the brute force method of sampling as often as possible to insure that significant data is not missed. This is especially important when the maximum and/or minimum values of the data are significant in the experiment.

Channel Modulation

In the currently available TDM TM units employed by Edwards AFB for parachute testing, the sample amplitudes from each channel are interlaced in time to serve as a modulating signal for the carrier. This interlacing of channel signals produces a series of pulses that is called Pulse Amplitude Modulation (PAM). While it is very easy to generate PAM signals, their linear nature makes them rather susceptible to additive noise distortion. This problem can be solved to some degree by using FM for the carrier to transmit the PAM signal. In fact, a PAM/FM TM system is used by Edwards AFB personnel for acquiring parachute test data. A better modulation type, however, is Pulse Code Modulation (PCM).

In general, the PCM process converts the amplitude of a sample to some signal with a finite number of states or levels. Usually, two levels are selected as the basis for containing amplitude information. This binary format is significantly more immune to additive noise effects than PAM because the additive noise must be of sufficient strength to alter a low level to a high level (or vice versa) before the value of the code will be altered.

Besides greater noise immunity, PCM offers several other advantages. One benefit is that repeated handling of the waveforms does not introduce any error unless the noise level is high enough to totally alter the code. This is because circuits that process PCM signals usually generate new, noise-free pulses rather than amplify a noise contaminated waveform. Also, the use of digital transmission realized from a PCM process can achieve TDM with no cross talk (Stark and Tuteur, 1979:162).

One problem that exists with PCM is that the continuum of input levels is converted to a discrete number of output levels. This error can be thought of as an additive quantization noise. Fortunately, the designer has considerable control over this form of error. By selecting smaller intervals, he can make the quantization noise component as small as desired. In contrast with this, however, is usually the requirement for faster hardware to accomplish the modulation process in the allotted time for each channel. As the interval between quantization levels is

decreased, the bandwidth of the PCM channel is proportionately increased because more information content is processed per unit time.

The Proposed System

The existing FDM and TDM TM systems used for parachute testing at Edwards AFB are of good engineering design and perform the required mission. Some problems encountered during use suggest that an improved parachute test data acquisition system needs to be considered. Many of the financial and engineering problem areas of these existing systems are centered around the telemetry setup. For example, during a crucial part of one experiment, a break lock occurred on the TDM TM system. Considerable additional effort was required to reconstruct some of the most significant data from the unsynchronized signal recording. Only through the use of extensive computer analysis of the received signal could the data be recovered.

Telemetry-based data acquisition systems represent proven technology in the field of data collection. Especially effective is the use of PCM as the means of carrying channel information. TDM/PCM gives a TM system multichannel capability with high noise immunity. Nevertheless, the use of TM in parachute testing requires access to a fully equipped test range. This means high test costs due to the amount and complexity of equipment, as well as personnel, necessary to support range operations. Therefore,

it is worthwhile to consider the possibility of data storage on board the data acquisition package. Of course, the harsh test environment of the data collection package would preclude the use of mechanical recorders, but recent advances in digital technology suggest that the sampled data might be stored in digital form. Since PCM is essentially the same in concept as the Analog to Digital (A/D) conversion associated with computer hardware, the concepts discussed above for PCM in a TDM system also hold true for a digitally-based DAS. In considering the nature of the hardware to be used in such a system, the use of special purpose devices may be necessitated by demands of overall system data flow rate. However, the use of a general purpose microprocessor deserves careful thought because of the device's low cost and inherent flexibility as a system controller.

It should be mentioned that a TM based DAS has one good feature in its favor: even if the test package is entirely destroyed, the data has been recorded at a remote location for later analysis. Self-contained DAS's must, therefore, be well engineered to insure that the survival of critical components is highly probable if the unit should freefall to impact. It has been the experience of personnel at Edwards AFB involved with parachute testing that the electronic modules often survive a free fall impact, but that connectors and other attached hardware often shear off. Such experience seems to suggest that a

properly designed self-contained DAS will very likely survive a free fall impact sufficiently to allow the collected data to be extracted.

Comparing Fig. 6 to Figs. 1 and 2 (or 3 and 4) combined, it can be seen that the use of on-board storage in a DAS considerably reduces the processes through which the data from the sensors must undergo compared to TM-based systems. Also, the early PCM process in the A/D conversion gives the signal high noise immunity. It is significant that storage of data in digital form means that automated data processing equipment can readily be used to analyze the data. This approach is much better than performing an A/D conversion on the telemetry data because noise effects may add significant error to the late A/D conversion process. It is strongly recommended that if computer data analysis is to be performed that the digitizing operation be accomplished as early as possible in the data acquisition phase. This implies that either PCM be used on sensor output in conjunction with a PCM/FM TM system or that A/D conversion of sensor values be performed and the digitized equivalents stored in on-board memory.

In Fig. 7, the control structure of the self-contained DAS is shown. The heart of the system controller is a general purpose microprocessor. The signal processor contains instrumentation amplification, bandwidth limiting hardware, and the A/D converter for all channels. The

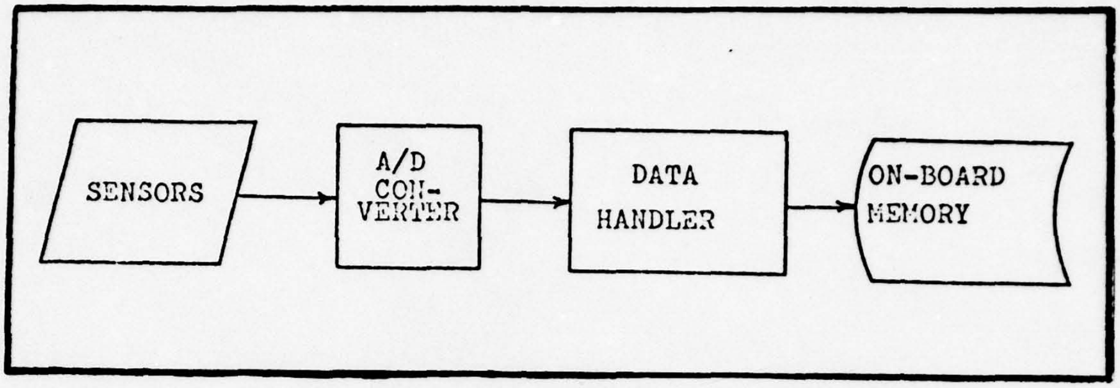

Fig. 6. Self-contained DAS: Data Flow

memory includes the memory device itself along with supporting hardware.

Channel Description

To evaluate the feasibility of a microprocessor-controlled, self-contained DAS, a complete description of the nature of the channel inputs is necessary. With the assistance of personnel at the Advanced Systems Division Wright-Patterson AFB, Ohio, a tentative channel description has been made. The description of the number and range of each channel is summarized in Table I. All listed channels (with the exception of the Events channel) are driven by sensors. The kinds of channels selected reflect a proposed capability of this DAS to operate in an environment free from both telemetry and cinetheodolite equipment in that all information which would be gathered from cinetheodolite tracking is instead measured with on-board sensors. It is important to note that all specified accuracies allow the digitized sensor information to be quantized as

TABLE I

Channel Description

Channel Type	Quantity	Range	Error
Force	2	0-4500 lb	18 lb
Dynamic Pressure	1	0-500 KEAS	2 KEAS
Low Speed Velocity	1	15-45 ft/sec	0.2 ft/sec
Pressure Altitude	1	0-20000 ft	100 ft
Linear Acceleration	3-axis	-25- +25 Gs	0.2 Gs
Angular Acceleration	3-axis	-600- +600 deg/sec	3 deg/sec
Events	1	Launch, DI, SSD, Impact	None

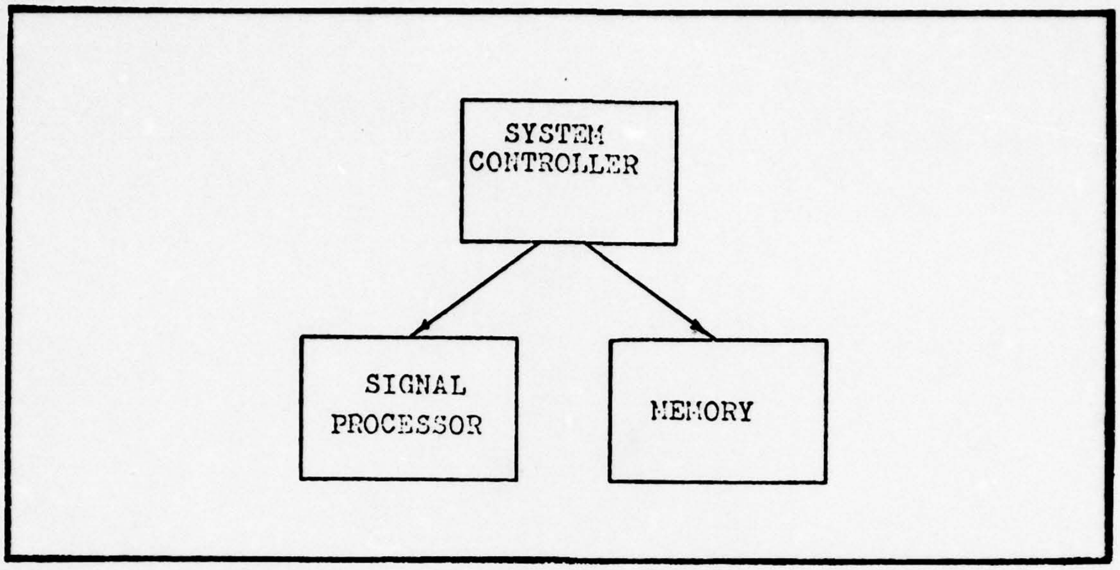

Fig. 7. Self-Contained DAS: Control Structure

an 8-binary digit (8-bit) quantity. This is useful because most popular microprocessors in current production are designed to function efficiently with 8-bit words. The Events channel is not a sensor output, but represents a system interface with supporting test hardware. An 8-bit word is capable of recording 256 events. This is well over the number required in typical parachute tests. Events considered in this evaluation are: Launch, Deployment Initiation (DI), Line Stretch, Steady State Descent (SSD) and Impact. Launch, of course, is the release of the test package from the aircraft. Deployment Initiation is the time when the parachute deployment hardware is first activated. Line stretch is the moment when the parachute canopy has first completely extended the suspension lines after deployment; this occurs prior to the beginning of canopy inflation. Steady State Descent is the somewhat

nebulous point where effects of the parachute deployment sequence have essentially disappeared, and the parachute and test dummy are falling in a steady state condition. For purposes of this analysis, SSD will be defined as approximately 30 seconds after DI. Impact is, of course, contact of the test package with the earth.

Description of Channel Sample Rates

In order to properly configure a proposed self-contained DAS with internal memory, it is necessary to carefully evaluate the impact that sample rate will have on memory size. Table II displays sample rates that would typically be needed to accurately recover the original sensor waveforms from their samples. This table was also prepared with the assistance of the Advanced Systems Division at Wright-Patterson AFB. Some minor changes were made to the original specification to simplify the system evaluation process, but the use of these modified specifications does not have any impact on the capability of the system to perform as specified. One modification to the specification required that the 1000 sample/second rates begin at DI rather than DI minus two seconds. This modification has been made because the system will be configured for testing as a passive data collector from an event standpoint. Thus, it would not know when the event DI minus two seconds would occur because it is not signalled until DI. Because DI involves a mechanical initiator on the

TABLE II

SYSTEM EVENTS DESCRIPTION

Channel Type	Power up to launch (TEST)	Launch to DI	DI to SSD	SSD to Impact
Force	1 sample/sec	None	1000 samples/sec	None
Dynamic Pressure	1 sample/sec	10 samples/sec	10 samples/sec	None
Low Speed Velocity	1 sample/sec	None	1 samples/sec	1 sample/sec
Pressure Altitude	1 sample/sec	10 samples/sec	10 samples/sec	1
Linear Acceleration	1 sample/sec	None	1000 samples/sec	None
Angular Acceleration	1 sample/sec	None	None	1 sample/sec
Events	1 sample/sec	100 samples/sec	100 samples/sec	1 sample/sec

parachute pack, it is highly likely that the sample rate would change to 1000 samples/second before the first significant data from the deployment sequence could occur. However, there is no reason why this proposed DAS could not be configured in an active roll where the increased sample rate is initiated and then, two seconds later, the DAS signals the DI electronically.

The other change to the channel specification involves extending the 1 sample/sec rate for the low speed velocity channel (V_{LOW}) into the region between DI and SSD. Originally, the V_{LOW} channel was not to be activated until SSD minus five seconds. This modification to original specification was made for the same reasons described above and because the value of low speed velocity is significant in determining the first occurrence of SSD. Since it is sampled at a very slow rate, its impact on the momory budget during the region between DI and SSD is negligible.

As was discussed earlier, there is a relationship between the channel sample rate and its required bandwidth. Signal conditioning performed on a channel tends to dictate a minimum sample rate to prevent aliasing. This seems to contradict the use of the Pressure Altitude (PA) channel at both 10 samples/second from DI to SSD and 1 sample/second from SSD to impact. From an engineering standpoint, either the specification should be altered, or there should be some method to alter the cutoff frequency of the signal conditioner in the region from SSD to impact. However, since

the rate of descent is very much less (hopefully) than during free fall and because the PA channel is a continuously decreasing waveform, this situation will present no problems in reconstructing the sensor information from its samples. This problem does not present itself in the Events channel because it is not driven by a sensor.

Tentative Memory Budget

Of crucial importance in the design of this DAS is the need to determine the order of magnitude of memory required. By specifying the word size and the sample rates of all channels, the total memory needed for recording all data can easily be determined. In the region from power up to launch, the system performs a self-test and no data is stored. From launch to DI, the total number of samples/second is 120. The time interval of this region is not specified, but it ranges from zero to approximately ten seconds. (Longer time intervals have been used in actual parachute tests, but, as will soon be evident, the memory budget for this time interval will be negligible compared to other regions.) For up to a ten second interval in this region, 0.01 megabits of storage are needed.

In the region between DI and SSD, the overall sample rate is 5121 samples/second. The use of 8-bit words for 30 seconds (by definition of the interval) requires 1.23 megabits of memory. The last region involves a total sample rate of only 6 samples/second, but the time interval

can be long. For a 500 second interval, 0.024 megabits of storage are needed.

From the memory budget of a typical parachute test drop, it can be readily seen why such self-contained DAS's are not found in present use. Technological advances in memory devices, however, have made considerably larger memory sizes available to be used in systems.

The memory budget above should only be used as an order of magnitude figure because this represents an absolute minimum value. Other factors such as the memory required for software used to control the DAS and possible extra memory required due to the data structure should also be considered before setting the memory size of the DAS.

Concept Summary

It has been shown that a digitally-based DAS which stores the sampled data in internal memory is conceptually the same as a PCM TM system. A PCM TM system is superior in most respects to PAM and FM TM modulation, but there are still potential problems with the use of TM equipment. The TM hardware to overcome these problems becomes very expensive to build and operate.

III. System Hardware Design

It has been shown that a digitally based data collection system with on-board data storage is valid in concept. To determine whether such a system is possible with currently available hardware first requires an overview of the different types of memory devices.

Traditionally, the memory devices with the highest storage capacities are those that store information on a moving magnetic media. This class of memory device includes disk and magnetic tape. As discussed earlier, these devices have a number of critical tolerance moving parts which are not suited for a parachute test DAS. Another widely used memory type is core memory. This storage media retains digital information by residual magnetism imposed on tiny toroidal cores made of ferrite (Kline, 1977). This type of memory has an advantage in that stored information is non-volatile, but relatively low storage density, high power consumption, and somewhat frail structure make this type of memory undesirable for portable systems.

Semiconductor memory suitable for storage and retrieval of data can be classified into three general types: bipolar, Metal Oxide Semiconductor (MOS), and Charge Coupled Device (CCD) memory. All of these memories are volatile. Bipolar memories tend to consume more power

than MOS and CCD, but bipolar devices are generally faster than MOS or CCD. An advantage of MOS and CCD memories is that they have higher bit densities than comparable bipolar memories. A drawback of MOS and CCD types, however, is that they are dynamic devices: every so often the value of each memory cell must be refreshed with its old value to insure that information is not lost.

A relatively new memory device is the Magnetic Bubble Memory (MBM) (Bursky, 1979a). Digital information is represented as the presence or absence of magnetic domains within the device. During the fabrication process, these domains are configured so that they can be moved within the device in a manner similar to a continuous loop shift register. It is this routing structure, deposited on a garnet substrate, that determines the configuration of a particular MBM. Data within the MBM is non-volatile because of a magnetic bias field (supplied by two permanent magnets within the device). Information is made to move within the MBM by applying driving signals that create a rotating magnetic field. MBM data is stored and retrieved in a serial manner even though internal configurations often exist where some transfer operations occur in parallel. While it is possible in theory to organize a MBM in a strictly serial configuration, most commercially available MBM's are configured with either major-minor loop or block-replicate architectures (Bohning, 1979:115-116). This is done to enhance access time as well as to

improve production yield. Because of the technical difficulties in manufacturing the near perfect crystalline structures required for MBM devices, production units are allowed to have a small number of defective loops. In the major-minor loop architecture, data is transferred into the unit in serial format. This data is entered into the major loop. Data in the major loop can be transferred into the minor loops at the proper time. This process is reversed to read or overwrite data within the MBM. The block replicate structure is basically similar to the major-minor loop configuration, but input is split into two tracks for just the even or odd bits of the serial input word. These bits are routed to corresponding even and odd blocks which are comprised of a number of loops which make up the majority of the memory. Using separate read gating with a block replicate structure allows for faster data transfers to be accomplished.

In comparison with the semiconductor devices described above, MBM's have the highest level of integration available today. Commercially available MBM's hold 256K bits, and 1 megabit devices are soon to be marketed. Typical CCD's and MOS units hold 64K bits while bipolar devices have 16K bit storage (Bhandarkar, 1979:93).

Memory Type Selection

Of the semiconductor memories, the CCD has the greatest potential for mass storage applications. The

CCD has a relatively high level of integration, low power consumption, and maintains an acceptable access time compared with similar memory devices. Of particular importance in a portable system is having a device with relatively low power consumption along with high storage capacity. Thus, of the memory devices currently available, either the CCD or the MBM offer the greatest potential in portable data acquisition systems.

It is interesting to note that the CCD is also a basically serial device like the MBM. In fact, configuration within CCD's can also take on different forms and is roughly analogous to the loop-type patterns which exist within MBM's. Access times and data transfer rates for CCD's are much faster than available MBM's. Power consumption for a single 256K bit MBM is roughly twice that of a 64K CCD, but it would take four CCD's to hold 256K bits of data. Of course, since the MBM is nonvolatile, it can be shut down between reads or writes, but typical CCD devices will draw between 0.03 and 0.1 watt while idling (Bhandarkar, 1979:95).

More meaningful is the comparison of these devices when integrated into a system. For example a 1 to 4 megabit memory unit comprised of CCD's would typically have a data transfer rate of 1 to 32 megabits/second while a similar unit made up of MBM's would handle data at 0.1

to 1.6 megabits/second (Bhandarkar, 1979:95,96). Of course transfer rates depend significantly on how the devices are configured within the system. Serial configuration would result in the simplest support circuitry with a correspondingly slow data transfer rate. Conversely, a parallel architecture would result in high data flow rates, but hardware support would be more complex and the system configuration might be unwieldly to manage. The optimal configuration would most likely lie between the two extremes for most applications. Power consumption for this 1 to 4 megabit system would typically be 20 to 30 watts for a CCD-based unit while it would be 10 to 20 watts for a module with MBM's (Bhandarkar, 1979:95,96).

From the above discussion, it can be seen that the choice between the use of MBM and CCD in a portable DAS is not clear cut. For data collection at very high data flow rates over a relatively short period, the use of CCD's is indicated because of the importance of having a high transfer rate. However, for data acquisition involving slow data flow rates over a relatively long time, then the MBM should be employed because it can be powered down between acquisitions. In collecting data from a parachute test drop, the dynamic nature of the testing process makes the selection of a suitable memory device even more difficult.

The MBM has been selected for use in the proposed system because it has more memory capacity per device than

any other currently available type of memory. In addition, 1 megabit MBM's will probably become readily available before even 256K CCD's can be obtained. This means that a four-fold increase in system capacity could be expected soon with only minor system redesign. Another advantage to the MBM is that it is non-volatile. If the system is damaged in a freefall, it is quite likely that the critical MBM components would still be functional. With little additional effort, the collected data could be extracted from the damaged system. If CCD's were employed in a parachute test DAS, once the power to the CCD's is removed the collected data is lost. From experience with freefall malfunctions at Edwards AFB and its effect on parachute test DAS hardware, it is highly probable that power will be removed from the system if it contacts the earth at speeds approaching terminal velocity. Finally, the MBM has been selected because of previous work at Air Force Institute of Technology as well as efforts by National Aeronautics and Space Administration (NASA) in the development of a data recorder based on magnetic bubble memory devices. Initial efforts at employing MBM's in data acquisition packages (Bohning, 1979; Hill, 1978; Hoffman, 1976; 1976b; Jolda, 1977) suggest great potential for these devices in the data acquisition field.

For the sake of completeness, it should also be mentioned that several other types of memories were

examined for their potential in a portable DAS. From a power consumption standpoint, the use of Complementary Metal Oxide Semiconductor (CMOS) memory was investigated. Their very low standby power offers great promise for future DAS applications, but the present low level of device integration (currently around 1K bits per device) makes the use of such devices impractical for present systems. Another very promising development under development today is the Electrically-Alterable-Read-Only-Memory (EAROM). Unfortunately, these devices presently have limited lifetime, slow write speeds, and low levels of device integration which make this type of memory unsuitable for data acquisition applications (Wallace, 1979:130-131).

Potential for Microprocessor Control

The basic idea of collecting data, digitizing it, and then storing it is quite simple. This simplicity can be reflected in the hardware design. A relatively simple circuit can be designed that sends the appropriate channel number to an A/D converter, waits for the conversion, and then stores the digitized signal in memory so that the data can later be associated with the proper channel and the time of the data sample. Such hardware has the potential for high speed signal processing, but it might also be very expensive.

The main drawback to such a system is that it is very limited in the kinds of data manipulations that can

be accomplished. The nature of the data acquisition process is fixed (or at least limited) by the system hardware design. Of course, enhancements are possible to make a given hardware design more flexible, but this may add considerably to the complexity of the hardware. An interesting alternative is the use of microprocessor control.

With microprocessor control, the hardware consists basically of system modules interconnected by lines of control. The microprocessor commands the A/D process to commence and handles the data storage problems. System performance is determined by the software instead of hardware configuration. This greatly adds to the flexibility that the system possesses and may even allow the system to interact with incoming data. This represents a powerful capability when compared with a simple passive data collection system.

Since a software controlled system responds to the execution of a sequence of machine instructions, microprocessor control will usually not be as fast as special purpose hardware in accomplishing the same tasks. For example, it may take the execution of several instructions to determine which channel is next to be sampled, several instructions to command the A/D conversions, and several more to store the data. In fact, difficulty may be encountered in performing all of the required operations in the allotted time. Using the prototype system channel

description (see Table II), the highest data flow rate is 5121 samples/second in the interval from deployment initiation to steady state descent. This means that 195 microseconds can be allocated for each sample during this interval in the test. To determine the capability of a general purpose microprocessor, three popular microprocessors were selected: the 8080A, 6800, and 6502. Since the time for a given instruction depends on its type as well as the chosen microprocessor, the shortest and the longest times for execution of any instruction on a given microprocessor can be averaged to arrive at an approximate instruction execution time for a typical microprocessor chip. The result is that an average instruction takes 2 to 11 microseconds (Osborne, 1976: 4-2, 6-2, 7-2). This means that in the allotted 195 microsecond interval between 17 and 97 instructions can be executed. The length of the average instruction in typical programs depends somewhat upon application, but many programs can be coded in such a way as to keep the average instruction execution time below 5 microseconds. Based on a rough average of 5 microseconds per instruction, a 195 microsecond window would allow approximately 35 instructions to be executed.

It should be mentioned, however, that enhanced 8080A, 6800, and 6502 microprocessors are available that function at twice the speed of the standard chip. Thus,

the 35 instructions per sample can be viewed as a guide in implementing actual software rather than an absolute upper limit. It can be seen that data pre-processing (manipulation of data prior to storage) during the interval from deployment initiation to steady state descent must be held to a minimum, but from launch to DI only 120 samples/second are taken, and from SSD to impact only 6 samples/second are needed. This means that from launch to DI over 1600 instructions can be executed per sample, and from SSD to impact over 33000 instructions can be executed per sample. During these periods especially, the use of microprocessor control can greatly enhance system capabilities to interact with its environment in an intelligent manner.

A/D Converter Interface

Another important aspect of the overall data acquisition problem for the proposed system is the manner in which analog output from a sensor is converted into a digital equivalent. Another factor in determining the maximum data input rate of a system is the time it takes the A/D converter to actually perform the A/D conversion. A number of methods for A/D conversion are based on an electronic integration method that compares the time integral of a value over a known time to the same integral of a known standard charge (Lancaster, 1975:306-310). Such conversions have great potential for very high accuracy, but conversion times are much too long to be

used in the proposed system. Typical A/D conversions for devices based on this method are measured in milliseconds.

For higher speed applications, the method of successive approximation A/D conversion is used. This technique employs a systematic search for the unknown input voltage with each succeeding attempt determined from a comparator circuit within the A/D converter. The unknown signal is compared to an analog signal generated by an internal Digital to Analog (D/A) conversion of the binary value that is being tried. For example, an A/D converter might first try 1/2 of rated full scale input. If the internal comparison indicates the unknown is greater than the signal generated by the internal D/A converter, then 3/4 of rated full scale is tried next. Conversely, if the comparison indicates that the unknown input is less than 1/2 full scale, then 1/4 of full scale is attempted next. This successive halfing of possible input values continues until the converter converges to the proper value (within quantization error). With this method, conversion time is primarily a function of the number of bits required from the A/D process (because each additional bit requires an additional A/D conversion for convergence to the most accurate digital equivalent of the analog signal). This relationship assumes, of course, that only the number of bits of a successive approximation A/D converter is being varied and that the speed of the

hardware is held constant. Commercially available successive approximation A/D converters have typical conversion times from 10 to 500 microseconds with the faster converters consuming the most power. This general rule of thumb is important to remember when designing the A/D section of a portable system.

The fastest A/D converters are called flash converters. The principle of operation for this class of converter is simple: within the device, a comparator exists for each possible digital value. For instance, an 8-bit flash converter would have 256 comparators: one for each possible analog value of the input. In the past, flash converters were very expensive, bulky, and consumed significant power. Today, entire flash converters are becoming available with all circuitry in one Integrated Circuit (IC). Conversion times for these new devices are less than 1 microsecond (Datel, 1977:15).

When more than one sensor channel must be digitized, it would be possible to use an A/D converter for each channel. For most applications, this approach is wasteful because sufficient time exists to process one channel at a time. Most commercially available multichannel A/D converters multiplex the analog channels in time and feed the result into a single A/D converter. This configuration is much simpler and, therefore, yields

smaller, lower power devices than would be possible if multiple A/D converters were to feed a digital multiplex circuit. Until recently, multi-channel successive approximation A/D converters were made up of a single printed circuit board encased in a protective container about the size of a standard audio tape cassette. These units usually consumed from 2 to 10 watts and cost hundreds of dollars. Today, monolithic multi-channel A/D converters are available with similar performance but at roughly one tenth the cost of the older units. Especially impressive is the new generation of monolithic CMOS multi-channel A/D converter with conversion times on the order of hundreds of microseconds and with power consumption of less than one watt (National Semiconductor, 1978:2-29). Such devices are another reason why the future of digitally-based, portable data acquisition systems is so promising.

An important part of any good A/D converter is a sample-and-hold circuit. This section in the converter package performs a very brief sample of the analog signal and holds that value during the A/D conversion process. A varying input to a successive approximation A/D converter will cause the circuitry to converge to a value that exists during one instant of the conversion interval rather than at the initial instant of the sample. This effect is surprisingly important in that it significantly

limits the maximum frequency at which the A/D converter can successfully sample because the precise time of the sample is not known. For example, an 8-bit A/D converter has a conversion time of 50 microseconds: with sample-and-hold the maximum frequency component that can be accurately sampled (by sampling theory) is 10000 Hz; without sample-and-hold circuitry the maximum frequency component that can be accurately sampled is 12 Hz. The importance of sample-and-hold circuitry is also reflected in the fact that most multi-channel A/D converter units have built-in sample-and-hold circuitry.

As was discussed earlier, the highest data flow rate of the prototype system is 5121 samples/second (which is equivalent to 195 microseconds/sample). The A/D conversion time must, therefore, be less than 195 microseconds for all the signals to be processed at the maximum speed at which the system must collect and store data. At first, it might appear that the A/D conversion must be done in significantly less than 195 microseconds in order for the microprocessor to have time to execute the required instructions for processing the data. By means of a hardware interrupt to the microprocessor, it is possible to configure the system so that the microprocessor need only signal the start of an A/D conversion. Then, the microprocessor is free to handle other system tasks until the A/D converter signals completion of the conversion

by the interrupt mechanism. There is a small penalty to pay for overhead in the interrupt handler routine, but the interrupt capability means that the microprocessor need not wait on the A/D conversion.

MBM Utilization in a DAS

Unfortunately, the significant advances made in the area of A/D converters have not also been observed in magnetic bubble memory technology. There are many promising things for MBM's in the near future, but such devices do not exist as production hardware at this time. Rockwell International and Texas Instruments are presently the only commercial manufacturers of MBM's. Both manufacturers' devices hold approximately 256K bits of data.

Neither company offers hardware that can be efficiently used directly in a final version of a portable DAS, but the modular system that Rockwell offers is well configured as a research and development tool for MBM applications. The heart of the Rockwell development system is the MBM linear module (RLM658). This unit is a 9.75 by 6 inch printed circuit board containing four Rockwell 256K bit bubble memory devices (RBM256), a defective loop mapping Programmable Read Only Memory (PROM) to indicate the defective loops in each MBM, and all supporting circuitry necessary to control the MBM's. The memory is configured as 4 bits in parallel: that is, each MBM

stores a bit of a 4 bit word. Of course, other linear modules could be added to increase the size of the memory word by multiples of four to increase the overall effective data flow rate, or additional modules could be added as additional memory blocks. Commands to the linear module are in terms that an MBM and its supporting hardware would understand (i.e., generate, transfer in, replicate, read/write, etc.) (Rockwell/RLM658, 1978).

To integrate the linear modules into a single memory package with microprocessor compatible commands, Rockwell has developed their RCM650 bubble memory controller module. This single printed circuit board is also 9.75 by 6 inches and can accept control for up to 16 RLM658 linear modules. Interestingly, the controller itself is built around a microprocessor. Also included on the controller board is a PROM that contains a driver program that makes the bubble memory function like a disk file system. This program is compatible only with Rockwell's System 65 development system, but this program is not an essential part of the controller in that the board can be used with other compatible bus interfaces such as the Motorola Exorciser series (Rockwell Control Module, 1979).

The Rockwell bubble memory development system has been designed to serve primarily as a ground-based, solid-state disk. For this reason, general-purpose integrated circuits were employed throughout the system rather

than special application hardware. This results in greater power consumption and larger board size than would be experienced if special purpose integrated circuits were used to interface with the MBM's. On the other hand, in a laboratory environment, the present Rockwell support hardware is easier to work with and maintain. The use of a microprocessor based controller is questionable in a portable DAS since the operations could be much more efficiently accomplished with straight hardware, but prototype DAS's may be able to incorporate bubble module control along with overall system control by redesigning the present bubble controller module. This means that the system microprocessor could also serve as the bubble controller microprocessor. Such implementation would only be possible in DAS's with very low data flow rates because a significant amount of microprocessor time would have to be devoted to handling the bubble memory module.

A problem also exists in directly employing the Rockwell linear modules in a portable DAS: it consumes too much power. While operating, the unit draws 13.5 watts and in standby mode the unit consumes 6.6 watts (Rockwell Control Module, 1979). In contrast, the Rockwell 256K bubble (RBM256) uses only one watt while operating and uses no power in standby. The high power consumption of the linear module is due predominantly to the fact that this module was not designed specifically for portable

systems and not because of inherent limitations of the bubble memory. This is also reflected by the fact that the linear module board cannot be totally powered down. Another limitation of the board design is that it is configured for forced air cooling to maintain the MBM temperature at or below 70 degrees Centigrade. While a portable DAS could also be designed to provide forced air cooling, the use of conduction cooling would probably simplify the cooling system significantly because of possible operation in an uncontrolled environment.

The designer of the cooling system in the final version of a parachute DAS may need to consider the problem of retaining heat more than losing it. For example, in high altitude drops from aircraft, the outside air temperature at altitude could easily be far below the lower limit for bubble operation of -10 degrees Centigrade. In this environment, system generated heat could be used to keep the package at proper operating temperature. Of course, these kinds of problems are present in the current generation of parachute DAS, but the designer of an airborne prototype needs to be fully aware of the potential adverse effects of temperature on the proposed system.

Despite the fact that bubble support hardware made up of general purpose integrated circuits has many advantages in a laboratory environment, a bubble development

system with specialized support hardware could not be procured for prototype experimentation because such systems do not yet exist. In the future, however, new generations of support IC's will be available from Rockwell, Texas Instruments, and other manufacturers that are not yet in the MBM production business. For example, Intel Corporation will soon be offering a 1 Megabit MBM which they call 7110. More significant will be their line of special purpose support chips: a 7220 controller, 7242 output sense amplifier, 7230 current-pulse generator, and 7250 coil driver. The controller is capable of handling up to 8 MBM's in parallel (for maximum data transfer rate) or in time multiplex configuration (for minimum power consumption). The current pulse amplifier incorporates power-down circuitry to shut off the current sources when the chip is deselected as well as a power-fail detection circuit to remove power from the MBM in a predefined fashion (Bursky, 1979:31-32). It is interesting to note that the 7220 controller employs High Noise Immunity Logic Metal Oxide Semiconductor (HMOS) fabrication. This means that the 7220 has all of the advantages of low power utilization of CMOS technology along with the protection from voltage transients that would render normal CMOS IC's inoperable.

Another limitation in the current generation MBM's is the significant power required to drive the field coils.

These coils create the rotating magnetic field that causes the magnetic domains to move within the device. Research at Bell Laboratories has produced an MBM that uses a different method to cause the domains to move. This technique promises to increase storage density by a factor of four, reduce device size, and reduce device power consumption (Bursky, 1979:32). Commercial production of these devices is at least one to two years away, however.

Perhaps the biggest problem facing the implementation of MBM's in data recorders is that there is not widespread interest in a new generation of data recorder. For this reason initial marketing of magnetic bubble technology has been in ground-based computers for use as a replacement for mechanical disk storage. Since many data collection tasks are accomplished in a relatively friendly environment, mechanical data recorders can be used successfully and economically. One area where mechanical data recorders have proven to be unacceptable is in spacecraft. In fact, in many cases, the data recorder has been the weakest link in the spacecraft.

For this reason, and because of the great potential of MBM devices, NASA is actively engaged in a program to develop a data recorder based on magnetic bubble memory technology. As part of this effort, the Applied Physics Laboratory at Johns Hopkins University developed a system architecture for a future MBM based data recorder for use

in spacecraft (Hoffman, 1976). Based on requirements of existing and proposed space programs, the following target specifications were proposed: 100 million bit memory, 100 thousand bits/second recording rate, 1 million bits/second playback rate, less than 20 watts consumed under maximum power condition, less than 10 pounds, and occupying less than 800 cubic inches.

It is interesting to compare these target specifications to those for the proposed parachute DAS. From earlier discussion of the required memory size for a typical parachute test (Plus allowing for an additional 100% for system expansion and test parameter variations) a requirement for four million bits of memory is obtained. At the maximum data flow rate, 5120 samples/second are taken and converted into 8-bit binary equivalents. This converts to 40960 bits/second or, in round figures, roughly 50000 bits/second data flow rate. The playback rate of the parachute test DAS is not critical because the data will be retrieved after the conclusion of the test. For comparison purposes, arbitrarily setting the playback rate at 50000 bits/second (same as record rate) will allow sufficient speed for expeditious data recovery. The power consumption for the proposed DAS is not specified, but, obviously, should be as low as possible. Similarly, the weight of the proposed system should also be as low as possible. Size and shape of the proposed system package is rather tightly constrained. In order to fit inside

existing test dummies, the package must be a cylinder of 2.5 inches radius and 23 inches long. The equivalent volume of this package is 451 cubic inches, but allowing 51 inches for internal mountings, case thickness, etc. leaves 400 cubic inches for actual hardware. It is safe to say that circular printed circuit boards suitable for use in this package will not soon be commercially available as this is a significant departure from the more or less standard 9 by 6 inch slide-in computer board. Despite fabrication difficulties, the spaced circular printed circuits within the cylindrical container has greater potential for survivability than the larger end-mounted rectangular boards simply due to the nature of board size and its mounting.

DAS Implementation Feasibility

While there are many differences between an on-board satellite data recorder and a self-contained data acquisition system, it is useful to compare target specifications to determine if there is a basis for comparison. It can be seen in Table III that the satellite data recorder target specifications exceed the proposed DAS specifications in all areas except volume. Thus, examining the design trade-offs of the proposed satellite data recorder can provide insight into similar factors influencing the design of a self-contained DAS.

TABLE III

TARGET SPECIFICATION COMPARISON

Parameter	Satellite Data Recorder	Proposed DAS
Bit capacity	100,000,000 bits	4,000,000 bits
Record bit rate	100,000 bits/s	50,000 bits/s
Playback bit rate	1,000,000 bits/s	50,000 bits/s
Power	$\leq$20 watts	$\leq$40 watts
Weight	$\leq$10 lb	$\leq$10 lb
Volume	$\leq$800 in^3	$\leq$400 in^3

In the conceptual design of a bubble memory satellite data recorder by the Applied Physics Laboratory (APL) at Johns Hopkins University (Hoffman, 1976; 1976b), considerable attention is given to the internal configuration of the magnetic bubble device. In contrast to the internal recirculating MBM's that are typical of the majority of MBM devices offered today, APL recommends the use of MBM's with non-recirculating structure. This requires that external circuitry be included to feed MBM output back into its input if the stored data is to be retained. The advantages for the use of non-recirculating chips include simpler chip design, more area on MBM chip for storage, lower fabrication costs, and higher device reliability. With non-recirculating MBM's, the data

recorder is based on chips with a capacity of 100 to 400 kilobits. This somewhat low figure reflects the fact that one megabit MBM's could not be fabricated when this design was undertaken.

In order to minimize the power necessary to drive the MBM coils, 8 chips are simultaneously controlled by one pair of driver coils. This configuration is achieved by having four chips arranged in a 2 by 2 array at the center of the driver coil pair. The four remaining chips are placed on the back of the substrate of the 2 by 2 array. Even with 8 chips being driven simultaneously, there is not enough parallelism to allow for a 1 million bit/second playback rate. By concatenating two 8-chip units to essentially form a 16 bit parallel word, the shift rate required for the MBM drops to a manageable 93,750 Hz in order to obtain a one million bit/second playback rate. To minimize power consumption, each 16 chip coil set is energized only when data needs to be transferred. In this design, 4 coil sets make up a page and 6 pages comprises all of data storage. It is interesting to note that just one page of this system has four times the required capacity of the proposed DAS. The MBM's and supporting circuitry for one page in the satellite data recorder is contained on one 9 by 4.5 inch printed circuit board with overall thickness (including components) of 0.75 inches.

The satellite data recorder has features which would not be useful for a DAS. For example, because the satellite recorder is not accessible for maintenance, it has built-in features to test for defective pages. If found, these faulty pages are then removed from use electronically. Page faults, along with values that mark the position in the memory where the next item will be stored, are held in a small non-volatile core memory. This allows for the system to be powered down without having to re-initialize all MBM's to some predefined position. This feature is particularly important when input data rates are slow enough to allow the MBM's to be powered down between storing successive data values. A somewhat surprising decision is made to use low power Transistor-Transistor Logic (TTL) instead of CMOS. However, even though the low power TTL consumes considerably more power than comparable CMOS devices, the radiation hazards in space make use of CMOS unadvisable (Hoffman, 1976b:100).

Weight Analysis

Because of the structure of the satellite data recorder, it is designed to work with less than all 6 pages. Since one page has only four times the storage capacity of the proposed DAS, the two systems are roughly equivalent if the satellite data recorder is

configured with only one page of memory. In Table IV, the system weight with only one page is shown. It should be mentioned that the control logic section is more complicated (and therefore heavier) than necessary because the satellite data recorder is designed to use more than one page. Thus, in an optimized design, one would expect the actual weight of the proposed DAS to be less than 6.4 lb.

TABLE IV

SINGLE PAGE SYSTEM WEIGHT
(Hoffman, 1976b:104)

Component Part	Weight (lb)
1 Page Memory	1.029
Control Logic and Power Supply	1.871
Miscellaneous Wire/Structural Parts	1.400
Shield and Case	2.100
Total Weight	6.400

Power Analysis

Since only one page of the satellite data recorder is powered up at any given time, an equivalent single page system would consume essentially the same power. Based on the number of IC's in the proposed satellite recorder, the worst-case power consumption is 9.8 watts. TM-based DAS's presently in use at

Edwards AFB are powered by 28 volt Ni-cad batteries rated from 1.2 to 2.2 ampere-hours (based on a 10 hour discharge interval). The telemetry packages typically draw between 1 and 1.5 amperes over time intervals ranging from 20 minutes up to one hour. This represents power dissipation ranging from 28 to 42 watts.

Reliablity Potential

With the assistance of the APL Space Reliability Group, reliability figures were obtained for one page of storage and for the system. The failure rate for the entire data recorder except for effects of a page is 2.16991×10^{-6}/hr. The failure rate for a page is 2.86130×10^{-6}/hr. Since the Mean Time Between Failures (MTBF) is the reciprocal of the sum of the above failure rates for a one page system, the MTBF of a one page system is 198759 hrs (or approximately 22 years). It is also interesting to note that, of the bubble memory components, the bubble chip is not the most failure prone. With a failure rate of 0.0300×10^{-6}/hr, the bubble chip has less than one-half the failure rate of either the coil driver IC or the generator loop IC (Hoffman, 1976b:105).

Cost Analysis

While comparing different systems with similar capabilities may be useful to provide insight into the potential for a proposed concept, it is probably not valid

to compare hardware costs between two systems with different applications. One would not expect the hardware in a parachute test DAS to be of the same overall quality as hardware used in space applications. However, by treating a parachute DAS as if it were a satellite data recorder, a cost may be arrived at which represents at least the price of a gold-plated parachute DAS. In Table V, price information from the satellite data recorder was manipulated to obtain an approximate (probably high) cost of a parachute DAS. The 9 electronic boards in the satellite data recorder has been reduced to 4 in order to represent a one page DAS. Also, the number of bubble chips has been reduced to the amount needed to hold 4 megabits of data. Since the custom IC's probably support MBM devices, they were proportionately reduced also. All other values remain intact even though the complexity of the satellite data recorder suggests that hardware simplifications are possible.

Thus, it can be seen that MBM's can be effectively employed in self-contained DAS's. The final system volume for the satellite data recorder is 270 in^3. This is well within the required 400 in^3 volume available for the parachute test DAS. In addition, data storage capacity, record rate, power consumption, and weight are well within target specification limits. Of equal importance, however, is the role of software in controlling system operation.

TABLE V

PROPOSED DAS COST ESTIMATE BASED ON SATELLITE DATA RECORDER (Hoffman, 1976b:107)

	Cost
4 Boards at $2000 each	$8000
15 Bubble chips at $50 each	750
10 Custom IC's at $50 each	500
155 Conventional IC's at $20 each	3100
192 Small electronic parts at $10 each	1920
Magnet assemblies, system housing, all mechanical parts	5000
Total Hardware Cost	$19270

IV. System Software Design

Equally important in the design of a proposed DAS is the nature of the software that controls the system functions. If software is not carefully designed, then data acquisition errors may result even though the system hardware is functioning perfectly. In a newly configured system especially, it may be very difficult to isolate whether hardware or software is the cause of a particular malfunction. A properly configured software controlled system, however, has the potential to provide for greater system utility because of its inherent flexibility.

System Support

In order to load programs into a microprocessor controlled DAS, to extract data from the airborne package after an experiment, and to perform tests and evaluations of system performance, some form of support equipment is necessary. This support equipment could be implemented as special purpose hardware. However, to do so would tend to limit the capabilities of a microprocessor controlled DAS because the support hardware would be much less flexible than the equipment that it supports. Thus, it is logical that if the DAS is microprocessor controlled then the support equipment should also be microprocessor

controlled. An obvious choice for support equipment would be a general purpose microcomputer.

The main reason for utilizing a general purpose microcomputer as support equipment is to provide the user with a more easily manageable interface with the airborne DAS package. For maximum efficiency the microprocessor in the microcomputer should be the same as the microprocessor within the DAS. Thus, software which is to be executed in the airborne DAS could also be executed on the support equipment. In addition, the support equipment would have programs to convert human-readable computer languages to machine language which could be loaded into the DAS. These programs can be broken into three classes: data acquisition, data extraction, and system test.

Data acquisition software is used during the actual experiment in which the DAS is employed. During each experiment, this software would create a data base from the experiment that would depend on such factors as number of channels, channel sample rates, and, of course, on the way in which the software stores the data in the MBM. Associated with each data acquisition program and unique data base would be a companion data extraction program. A third class of programs would be designed to thoroughly test all system functions. Ideally, the support equipment would be configured to supply analog inputs to the DAS to perform closed loop automated testing of the

DAS. It is desirable for the support equipment to be faster than the DAS in this application so that the DAS may be pushed to its limits of performance.

It should be realized that it would be impractical to have a unique set of software for each individual experiment because of the length of time required to fully test each software set. If possible, the nature of the data base should be standardized so that only one program is needed to extract the gathered data from an experiment. It is also highly likely that similarities between different experiments would also allow data acquisition software to be standardized into essentially one program. Different variations required for different experiments would simply require that some parameter values be altered rather than altering the data acquisition program itself.

The selection of a computer language with which to implement software control of the DAS is of great importance. Assembly language corresponds to a one-to-one relation between the programs that the microprocessor executes and the user creates. With assembly language the user is essentially dealing with the microprocessor on its level. This type of programming has the greatest possibility for efficient use of the microprocessor, but it also takes more programming skill. Use of efficiently coded assembly language in a DAS is essential if the system is to be used at the maximum data flow rates that the microprocessor can handle as the system controller.

Programming in a Higher Order Language (HOL) such as Basic, Pascal, FORTRAN, or COBOL allows the user to work at a much higher level in that one statement of HOL often converts to many machine language instructions. While programming in an HOL is generally easier than writing an equivalent program in assembly language, the resulting machine language generated from the HOL may not be coded as efficiently as possible. Nevertheless, because the user can code programs more easily maintained, use of an HOL is desirable for all applications where execution speed or limited memory size is not a factor.

Even though the use of an HOL would not initially be advisable in a DAS configured to gather parachute test data, HOL programs would be of great use in extracting data from the DAS after an experiment. In this case, highly efficient machine language is not essential, and the greater power of an HOL could be effectively utilized in a highly capable data extraction program. For example, the G force channel in the proposed DAS typically has a range from -25 to +25 G's. During the experiment, G values are converted by the sensor to a voltage range of 0 to 5 volts. The A/D converter, in turn, converts this voltage range to hexadecimal values from 00 to FF. Since the G values are stored in the MBM in this format, the data extraction program must convert the stored 8-bit value back to the units of the sensor (in this case -25 to +25 G's). This conversion could be a simple linear scaling of the digitized value, but more likely it would be

a conversion based on the actual performance of the sensor used in taking the measurements. Finally, the channel data would be displayed in tabular or graphical form for analysis by the user.

There is also the possibility of having software which performs an automated analysis of the sensor waveforms. Simple statistical analysis can be easily handled with microprocessor based support equipment. Highly sophisticated analysis is probably best performed on a large scale digital computer. Even if the microcomputer is not used for the analysis, it can assist in preparing the data in the proper format for the large scale machine.

Even though the data acquisition program that resides in the airborne package must be very efficiently coded to insure high data acquisition speeds, this does not mean that minor program variations to accommodate different experiments must be entered by hand. Eventually it would be hoped that software configuration would be well established and that some automated means could be used to alter program performance at a very high level. This would be a data acquisition oriented language which would allow the user to tailor the system operation based on experimental parameters such as sample rates, timing of sample rate changes, etc.

It is important to realize that while a software controlled DAS has great potential for flexibility, this

does not mean that software configuration should not be limited as much as possible based on the variety of experiments that must be performed by the system. That is, to achieve the most reliable, most easily maintainable system, the software should be specifically written to handle a specific type of data acquisition task such as the collection of test data from a parachute evaluation. Thus, by using good programming practices such as structuring the program into modular sections with minimal interactions and by automating system testing, software based DAS's can be made to function as well as any comparable hardware based system.

DAS Software Storage

Even though a DAS with bubble memory storage has millions of bits available for use, the MBM is not a very efficient place to store DAS software because of the relatively slow access speed of information from MBM storage. On the other hand, if the DAS software were stored in semiconductor RAM, then power could not be removed or the program would be lost. One solution to this problem is to initially store the system software in the MBM storage. When the airborne package is powered up prior to the experiment, a relatively simple program contained in a Read Only Memory (ROM) could load the DAS software into RAM. Another possibility is to have the majority of the system software reside in ROM or PROM

with only the alterable parameters stored within the MBM. If the configuration of the MBM makes it difficult to read from the bubble devices just prior to a test drop, core memory or EAROM could be used to store the variable parameters. This would be especially convenient if such support nonvolatile memory were also used to hold pointers for MBM loop conditions to allow the system to be successfully restarted from an unexpected power fail condition.

Data Base Design

The manner in which data is stored into the MBM can dramatically affect the capabilities of the DAS. One method is to assign a block of memory locations for each channel and then consecutively store data from each channel in its appropriate block. However, since the MBM is basically a serial access memory this method of data storage would be excessively slow. Therefore, data storage methods are considered that are based on the sequential storage of data.

The most efficient method of storing channel data is to consecutively store each channel value as it is obtained. After the completion of the experiment, the values of the experimental parameters can be used to associate a data value with its appropriate channel. Thus, each data value is associated (or tagged) with its appropriate channel number based on its position in the data base.

Although positional tagging is efficient in the data storage mode, there are some pitfalls to this method which may make its use inadvisable. For example, if a one-time hardware malfunction occurs, then channel values will be improperly associated due to the possible loss of at least one A/D conversion. Similarly, it is conceivable that a rarely observed software error could cause the loss of one or more channel conversions. This condition is analogous to a break lock in synchronization on a TDM telemetry system. Thus, while it is possible to submit the already digitized data for computer analysis to reassociate the data values with their proper channels, this condition does not represent one of the desirable features of a digitally based DAS.

An additional disadvantage of positional tagging is that outside controls cannot be used to alter the sampling rates because it may be impossible to determine from the data alone when the control signal was applied. It might be possible to store a special sequence of values to mark the application of the control signal, but when this sequence is being stored the system cannot store data.

Thus, considering that the DAS may be employed in an experiment that can be expensive to repeat, it is not unreasonable to include a certain amount of redundancy in the stored data if the increase in system cost is significantly less than the cost of duplicating an experiment.

One simple form of data tagging is to place the channel number immediately before (or after) the channel value. This storage method utilizes more memory than position tagged data, but the interspersed channel numbers identify each value. While it can be argued that it is possible for a hardware or software error to store the wrong channel value, the additional information stored in the data base may more likely lead the user to discover the nature of the error. Also significant is the fact that the addition of a single MBM device greatly increases the overall system memory capacity. Thus, the requirement for doubling the memory capacity is less important because relatively few MBM's make up the system memory.

If one word is used for a data value and another word is used for its channel number, then the tagged data format takes up twice the memory of position tagged data, and the data storage rate is essentially the same. This is because the channel value is readily available to be stored along with its associated data. This assumes, of course, that the A/D conversion time is considerably slower than the time necessary to store data into the MBM. If the number of channels is limited to 16, the binary representation of the channel number takes four bits. It is possible, therefore, to pack two channel numbers in one 8-bit word to save one word of memory for every two data values stored. This method can save a significant amount

of memory if a large volume of data must be stored, but the extra time must be available for the system to pack the channel numbers into one 8-bit word.

Equally important in retrieval of the data values is the necessity to associate each value with its sample time. As before, each data value could be associated with a time based on the position of the data within the data base. However, if the same group of channels is sampled at varying rates, then positional tagging alone would not allow the proper times to be associated with the sampled values. Of course, timing information could be stored as a separate channel, but sampling timing values at high data rates would significantly limit the data rates that could be obtained from other data channels. In the case of the parachute test DAS, the Events channel capacity is barely utilized. It is therefore possible to add timing information onto the Events channel as needed to accurately specify time intervals in the data base. This timing information could be derived directly from the microprocessor clock or from an onboard interval timer.

Parachute Test DAS Implementation Considerations

Because of the reliability and ease of using tagged data structures in a data acquisition package, some form of tagged data base should be used in the proposed DAS.

However, system hardware restrictions may force the use of more efficient data storage methods. For example, to use a tagged data base in a parachute DAS would require 4 megabits of memory (based on channel specifications described earlier). If Rockwell's 1 megabit bubble modules (RLM256) were to be used directly in the DAS, power consumption for the 4 megabit memory alone would be 54 watts. Thus, until new generation MBM's with more efficient support hardware are available, present realizations of a parachute DAS would have to use a position tagged data base bacause of the high power consumption cost for additional memory.

The amount of software to be carried in the airborne DAS should be efficient in terms of both execution speed and program size. Thus, software for the airborne DAS should be written in assembly language. However, software to be executed on the support equipment should, whenever possible, be coded in an HOL. The choice of a particular HOL should depend primarily on the kinds of programs that are to be written as well as the availability of supporting programs. For example, if a variety of useful graphics application programs are available in FORTRAN, then this language should be considered for the HOL. FORTRAN is also useful in many scientifically related applications, and it has capabilities that allow the user to easily specify the format of the output

listings. BASIC is the most popular language for microcomputers. While this language is similar to FORTRAN, the average BASIC implementation would have far less capability than FORTRAN. A relatively new language is PASCAL. Its block structure and capabilities provide the user with a powerful tool for implementing support software. PASCAL is similar to the proposed Department of Defense language ADA.

Eventually, it would be desirable to create a program in an HOL that would execute on the support equipment but interface the user to the airborne package. The purpose of this program would be to allow the user to easily reconfigure the airborne package for a particular experiment without having to work at the assembly language level. To simplify the DAS software, it should not have any capabilities that are not needed in the airborne environment. This might mean that the software would not be able to read data from the MBM's. This suggests that system software be stored in a PROM rather than in the MBM's. The PROM's could be loaded with the DAS software from the support equipment. Since power failure recovery capability is essential for the parachute DAS, some auxiliary nonvolatile memory would be included in the system for retaining parameters relating to the state of the MBM's. Thus, system parameters that are frequently changed could also be saved in the auxiliary memory. For the parachute

DAS, examples of such parameters would be sensor initial value ranges and channel sample rates over the previously defined event intervals. If such parameters were to be standardized for all parameters, then they could also be stored within the PROM.

V. Recommendations and Conclusions

It has been shown that the concept of a digitally based, microprocessor controlled parachute test data acquisition system is valid. The current generation of CMOS A/D converters can achieve the necessary sample rates for the proposed system channel specifications (see Tables I and II), and this type of device consumes little power. The basic data collection and storage tasks can be efficiently handled by typical microprocessors (such as the 8080, 6800, and 6502), but the relatively high sample rates in the interval from deployment initiation to steady state descent require that the system software be efficiently coded.

There are, however, several problem areas to be conquered before full scale engineering development of the proposed system should begin. First, although beyond the scope of this project, the sensor problem must be solved. Sensors do exist on the present parachute DAS for force, linear acceleration, and angular acceleration. Suitable sensors need to be developed and tested on a prototype for dynamic pressure, low speed velocity, and pressure altitude. Second, while the magnetic bubble memory is well suited to data acquisition applications, it still represents a relatively new technology. Presently available

devices do not have the special purpose IC support that is highly desirable for increased portability and lower power consumption. Such IC's would also support power failure recovery capability which is necessary for the proposed system

This is not meant to discourage research on future DAS's employing hardware that has present technology MBM's. Designers of MBM based DAS's should realize that a new generation of MBM device (and support hardware) is soon to be released. System design should not suffer because of ill-advised tradeoffs made to accommodate present generation MBM devices when future generations of MBM's are the real solution to the design problems. Specifically, designers should not be overly concerned with questionable schemes for saving 256K bits of memory when future generations of MBM's will be in 1 megabit increments. Similarly, elaborate schemes for power failure detection and recovery cause the designer to work on problems that future MBM support hardware will solve.

The overall proposed system hardware design is summarized in figures 8 and 9. Figure 8 describes how the hardware interfaces physically and functionally with the experimental environment. The application of internal power to the system (by remote control) creates a system reset that causes the microprocessor to begin executing

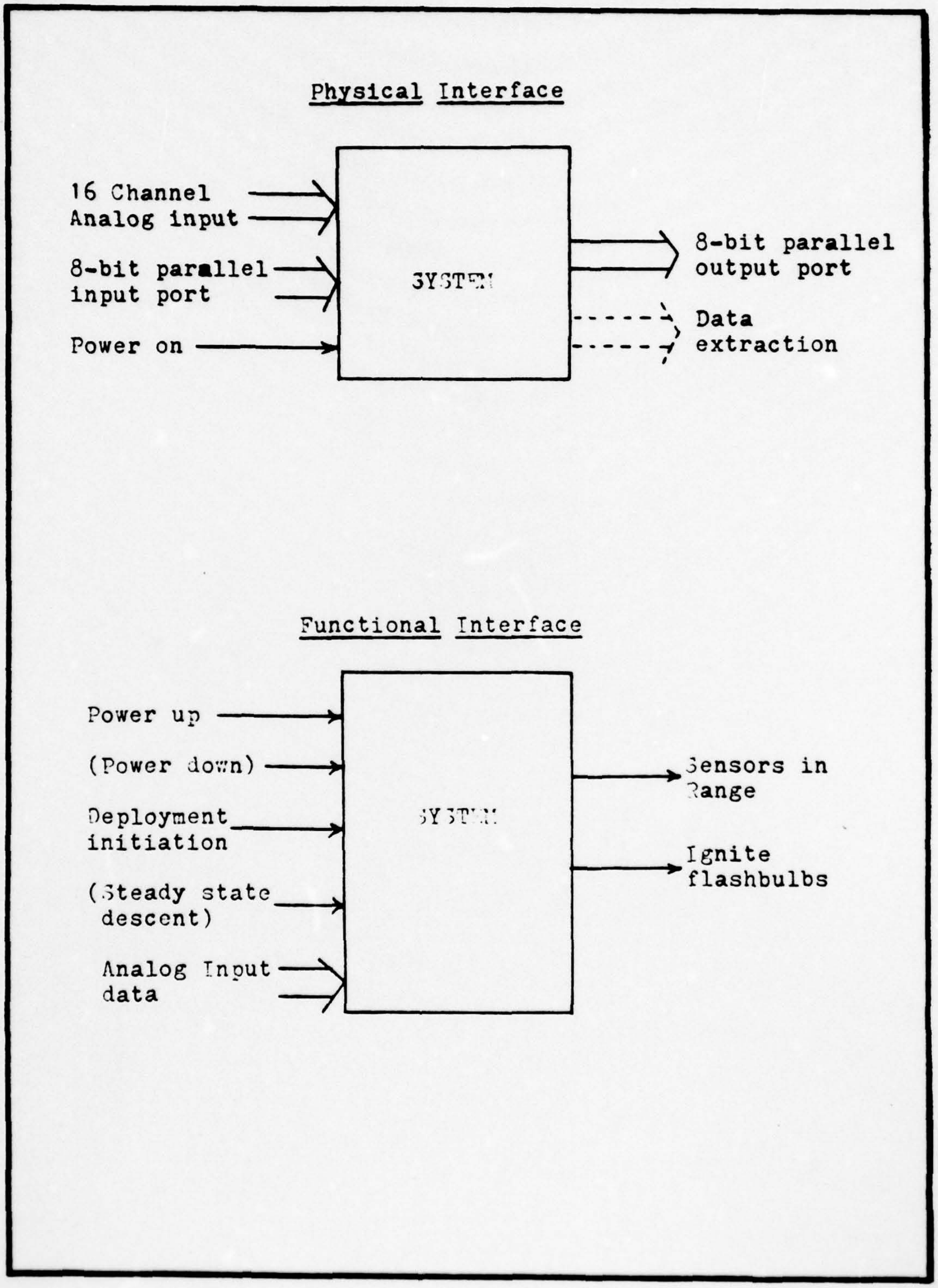

Fig. 8. System Interface

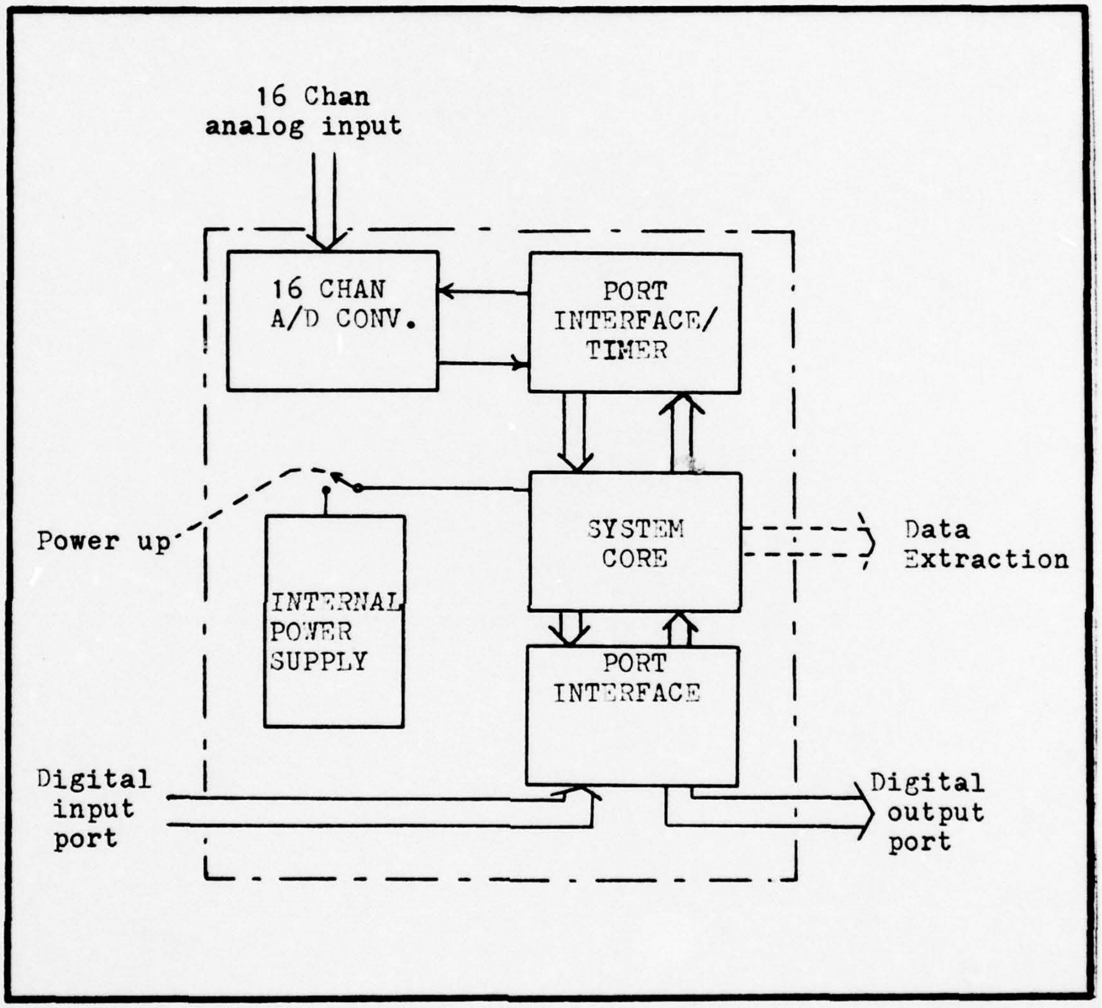

Fig. 9. System Internal Configuration

the program stored within the PROM. While the software will ultimately be responsible for powering down the system after the experiment, the capability to power down prior to launch might be important to allow for unplanned launch delays. In any case, such commands would be sent over the 8-bit parallel input port. Similarly, the launch command would be sent through the input port. This command would initiate channel sampling ard data storage.

During the experiment, the system would interact with the test hardware. For example, deployment initiation would signal the beginning of the high sample rates and cause the ignition of a set of flashbulbs mounted on the test package. This action would synchronize events within the DAS to events on the photographic record of the experiment. The initiation of steady state descent is an example of an event that is internally determined by the system software.

The dotted line for data extraction is to emphasize the primary role of the DAS. While software for extracting data from the MBM module can be included within the PROM, the fact that such software is present means that there is a possibility that the system may accidently enter the data extract mode during a test drop. Thus, the system configuration should not make it too easy to extract data from the MBM.

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EVALUATION OF AN IMPROVED PARACHUTE TEST DATA ACQUISITION SYSTE--ETC(U)
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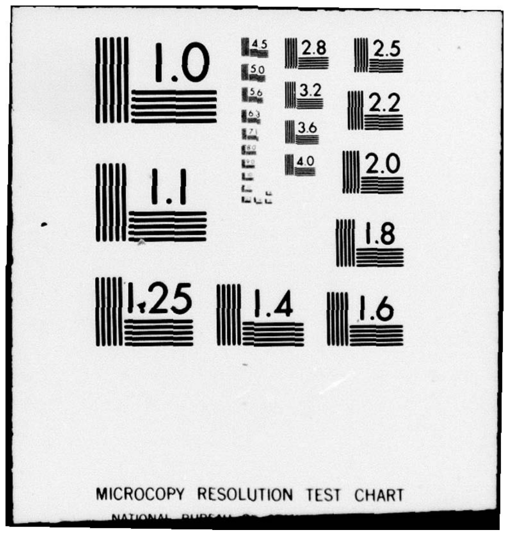
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MICROCOPY RESOLUTION TEST CHART

Figure 9 displays the suggested internal hardware configuration of the proposed system. Included in the system core is the microprocessor and its supporting hardware, the MBM storage module, the PROM that holds the system software, the scratchpad RAM for intermediate signal processing, and possibly an EAROM or small core memory for auxiliary nonvolatile data storage. The main purpose for this auxiliary nonvolatile memory is to store parameters related to MBM loop positions. This information is necessary to re-initialize the MBM loop positions prior to unloading the data obtained during the experiment. An alternate plan would be to re-initialize the MBM's prior to removing power at the end of the experiment. If this alternate option is used, then hardware must be able to detect a power failure condition in time to re-initialize all MBM loop positions. The connection for power-on reset is shown to emphasize the method of system program initiation.

The structure of the system software can take on many forms. One form that was implemented in a test program on a Rockwell System 65 is displayed in Figure 10. Program control proceeds from left to right in the modules immediately underneath the executive. The first module is entered when the system is powered up. Sensor testing is accomplished until the test package is released. The launch command initializes the data acquisition model and

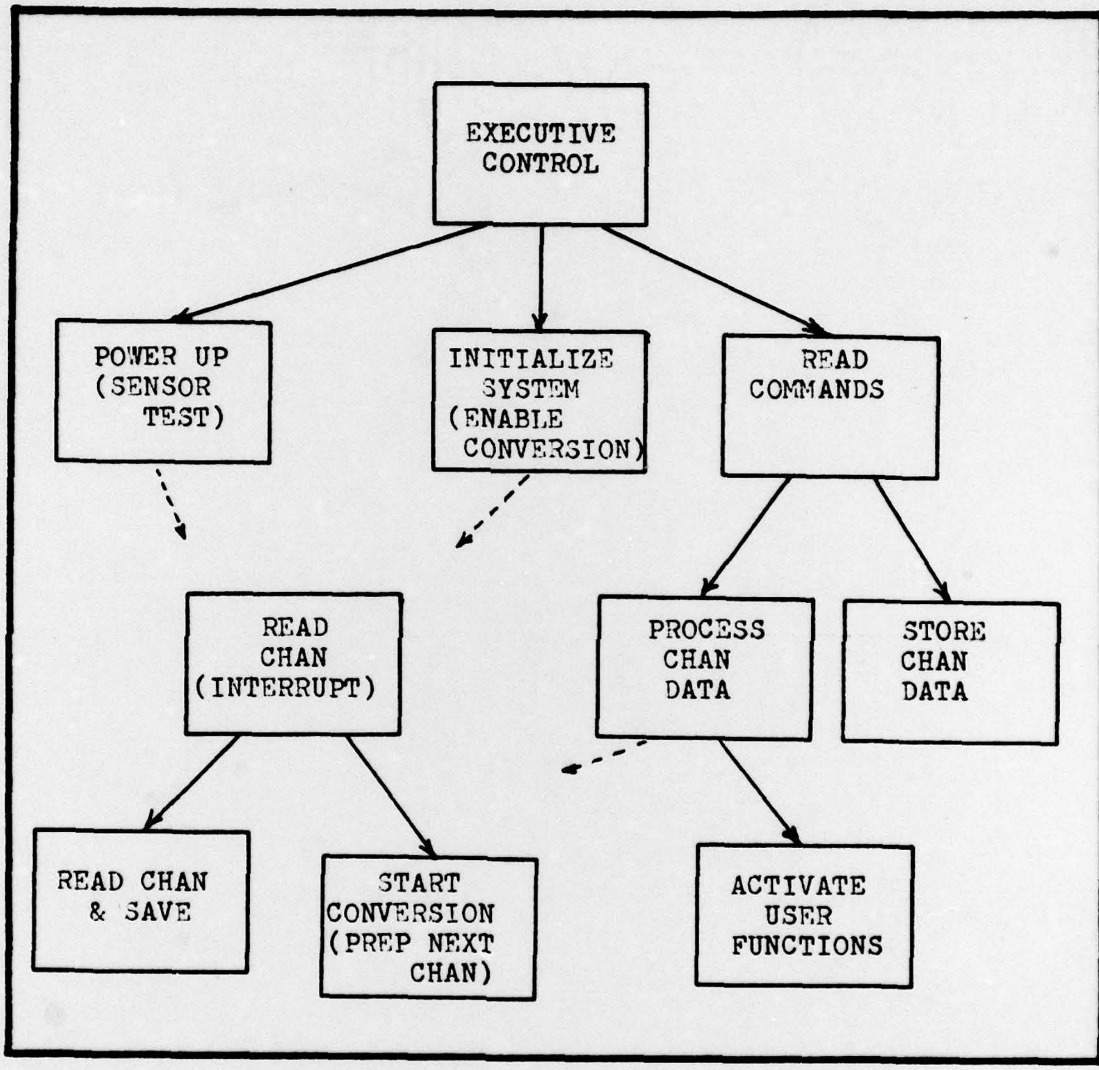

Fig. 10. System Software Data Acquisition Mode

causes channel data to be stored on the MBM. Because the Rockwell 1 megabit linear modules had not arrived for system testing, the data was stored in user RAM. The system remains in the data acquisiton mode until the MBM Module is full, the total experiment time is reached, or a minimum altitude is reached. The system as implemented with Rockwell's modules does not support hardware power failure detection, but sensor values (such as altitude) can be analyzed to determine the need to power down the system.

Since the Rockwell MBM's were not available, software has been written primarily to confirm that the A/D conversion rate is adequate to process the sensor data obained from a typical parachute test. These programs are coded in 6502 assembly language and in Rockwell's PL/65 HOL. These simulation programs confirm that data can be handled at high enough rates to demonstrate that the proposed system could be controlled with a general purpose microprocessor.

However, since Rockwell's MBM module controller board also uses a microprocessor, additional work needs to be done to determine if the functions of the system microprocessor and the bubble controller module can be combined in the airborne prototype.

Inquiries on specific programs and their results should be directed to the author or the Electrical Engi-

neering Department, Air Force Institute of Technology, Wright-Patterson AFB, OH 45433.

With this software structure the A/D converter causes an interrupt every time an A/D conversion is completed. The interrupt routine then reads the digitized channel value, and the main program is responsible for storing the data. Timing considerations may make this an unwise practice, in that saved data values may be overwritten before they can be stored. Thus, it is suggested that the interrupt routine be tasked with actual data storage. Every effort must be made to effectively utilize the A/D conversion time. For some A/D converter hardware, it may even be possible to start the next converson before reading the value from the last conversion. If possible, this would reduce the time between the end of the last A/D conversion and the start of the next.

Great potential exists for microprocessor control of self-contained DAS's useful for parachute testing. The proposed system is feasible from the standpoint of size, weight, and power consumption. Data flow rates encountered in parachute testing can be handled by general purpose 8-bit microprocessors, but considerable attention must be given to efficient algorithm coding to insure that high data flow rates can be managed. Use of assembly language coding is necessary in time-critical program loops to achieve maximum speed, but, if possible, HOL code should be used in program portions such as sensor testing

and power-up initialization where timing considerations are not as important. HOL should be used exclusively in the support system for programs like data extraction, manipulaton, analysis, and display. One exception, however, might be the need for assembly language code in developing real-time testing routines to be used by the support system to perform automated testing on the airborne package. The program structure should be aimed at ultimately achieving a data acquisiton oriented language to maximize the ease in configurating the system.

In the field of hardware design two major avenues are open with potential for markedly increasing system performance. One method is the use of new generation microprocessors to increase system performance. This includes not only 16-bit microprocesors with more powerful instructions sets but also special purpose microprocesors such as those with built-in A/D converters. Also included in this new line of devices is the new generation of programmable signal processors. Such devices could form the basis for a signal preprocessor which would allow only significant data values to pass to the system for storage. In this manner, memory space could be saved and the overall data flow rate would essentially be reduced.

An alternate method is to dedicate a general purpose microprocessor to each major system function for data processing with greater parallelism. While total system complexity would increase, the use of inexpensive hardware

could significantly reduce overall cost compared to a system with exotic, high speed devices.

Because the duration of parachute tests is generally no longer than twenty minutes, portable power sources are available that can more than meet system power consumption needs. For tests requiring longer time intervals, increasing attention must be given to the type of devices used in the system. The use of CMOS devices is recommended whenever possible to keep power consumpton to a minimum. When the proposed system is to be used in a potentially high intensity radiation enviroment (such as in satellite systems), of course, other device types should be considered.

Equally promising are the projected advances in magnetic bubble memory technology. As 1-megabit MBM's are entering the production phase, new generations of MBM's are being proposed with 4-megabit and possibly 16-megabit capacities (Reyling, Jr., 1979: 99). While these proposed devices may have lower average access times, it is most likely that future generations of MBM's will have higher data transfer rates, more capacity, and consume less power than present MBM's. It is estimated that a 4-megabit chip will probably be available around late 1982 (Reyling, Jr., 1979: 108).

Another aspect of MBM technology which is very important to the use of MBM's in data aquisition application is the introduction of LSI support chips for MBM

devices. These IC's can replace from 20 to 50 conventional semiconductor devices to achieve a significant reduction in package size, weight, and power consumption (Reyling, Jr., 1979: 102).

While other types of memory may eventually challenge the MBM's level of integration (notably CCD'with projected 256K bits per device), the MBM's nonvolatile storage medium would be a significant reason for continuing its use in portable data collection pakages even though CCD's may eventually become more cost-effective in a ground-based environment. The potential for digitally based data acquisition equipment is also demonstrated by the introduction of a new generation of sensors with digital output; thus eliminating the need for an A/D converter (Rao, 1979). Microprocessor and magnetic bubble memory technology will have significant impact on future data acquisition systems employed over a wide range of applications and environments.

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This project confirms the feasibility of a sixteen channel, self-contained data acquisition system that would be suitable to store data obtained during a parachute performance evaluation drop. The overall system is discussed in modular fashion to allow generaliation to other portable data acquisition systems that must accept data at high rates but over relatively short time intervals. The storage medium for the proposed system utilizes magnetic bubble memory devices.

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